Astronomical space observatories

From X rays to millimeter waves

Olivier Absil

F.R.S.-FNRS Senior Research Associate

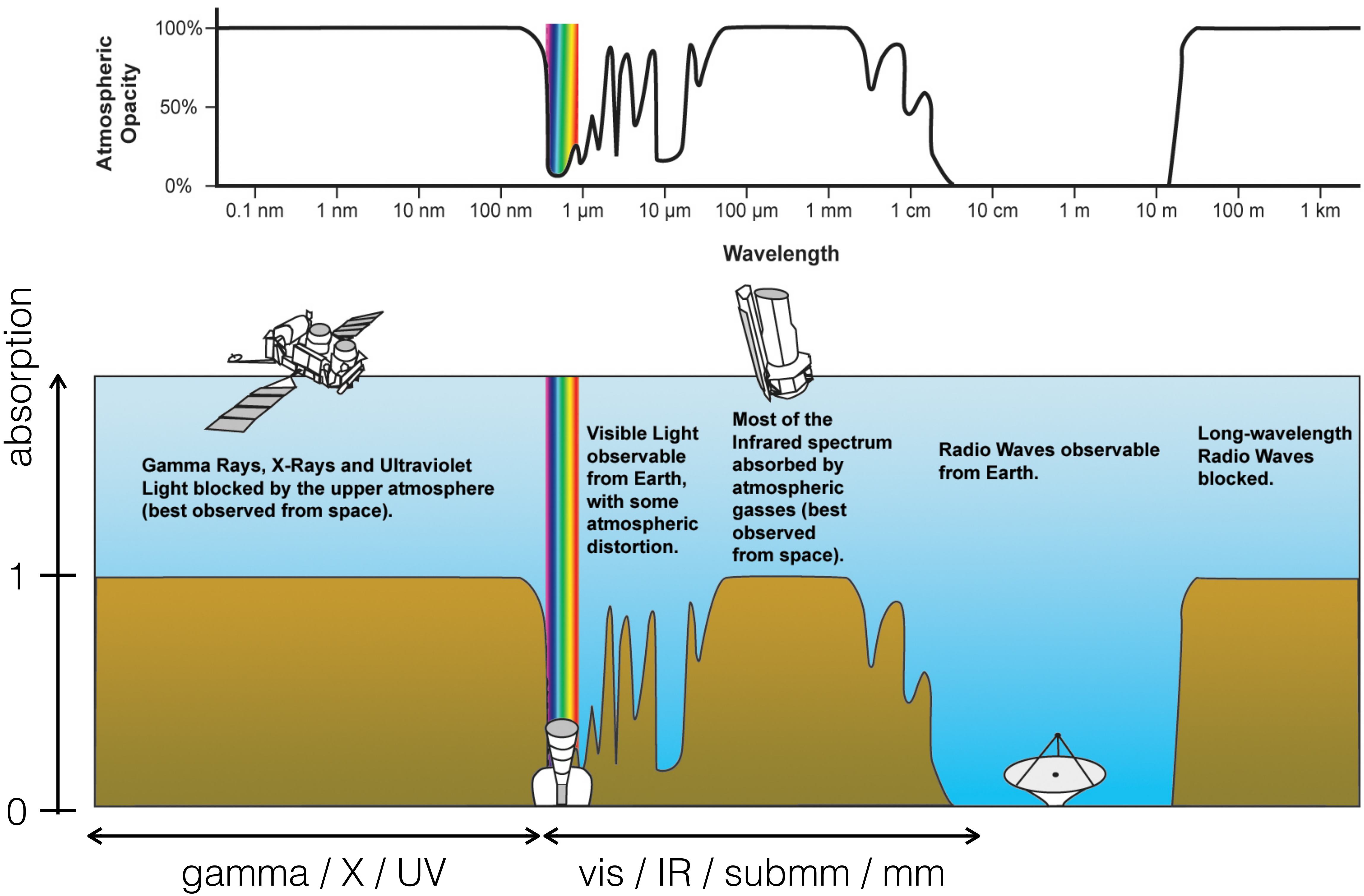
Space sciences, Technologies, and Astrophysics Research (STAR) Institute

olivier.absil@uliege.be

Why observing from space?

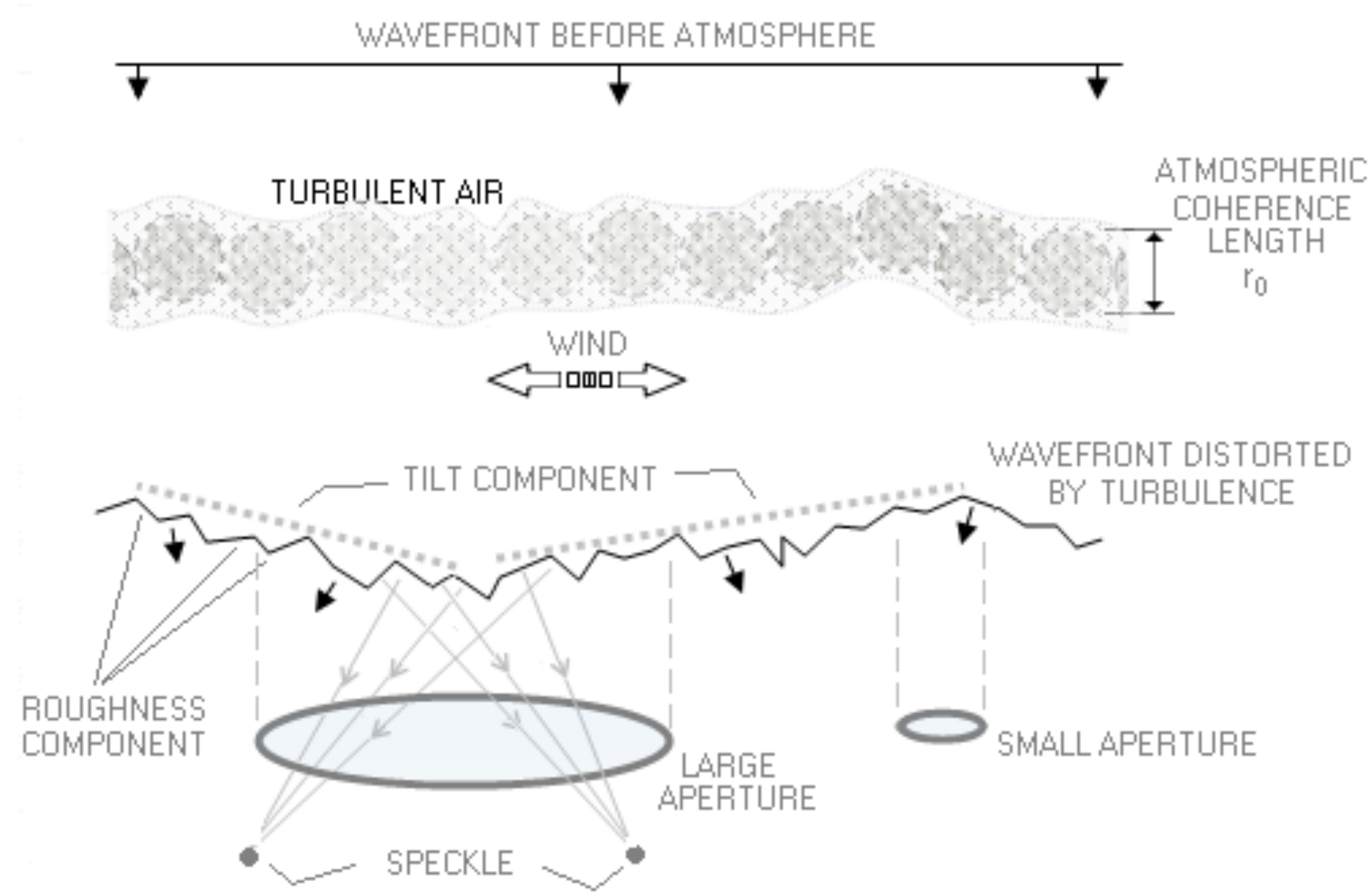
From X rays to millimeter waves

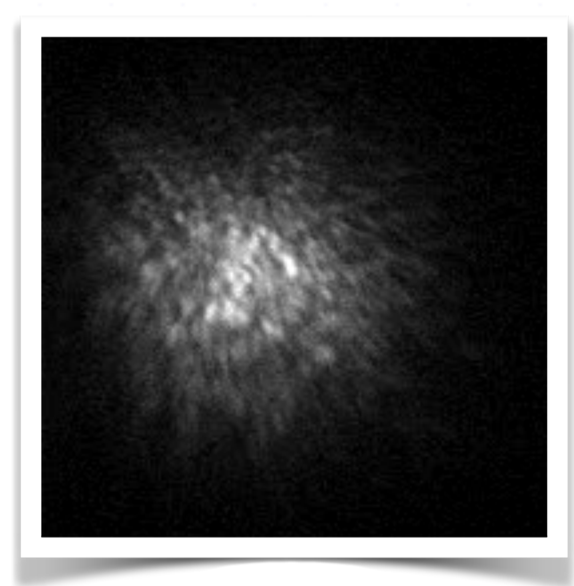
Atmospheric transmission

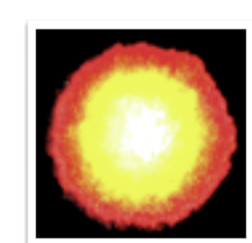


Atmospheric turbulence

- Corrugated wave front
- Image: spot size λ/r_0
  - r_0 = coherence length of turbulence (~10 cm)
  - resolving power limited to that of a 10-cm telescope





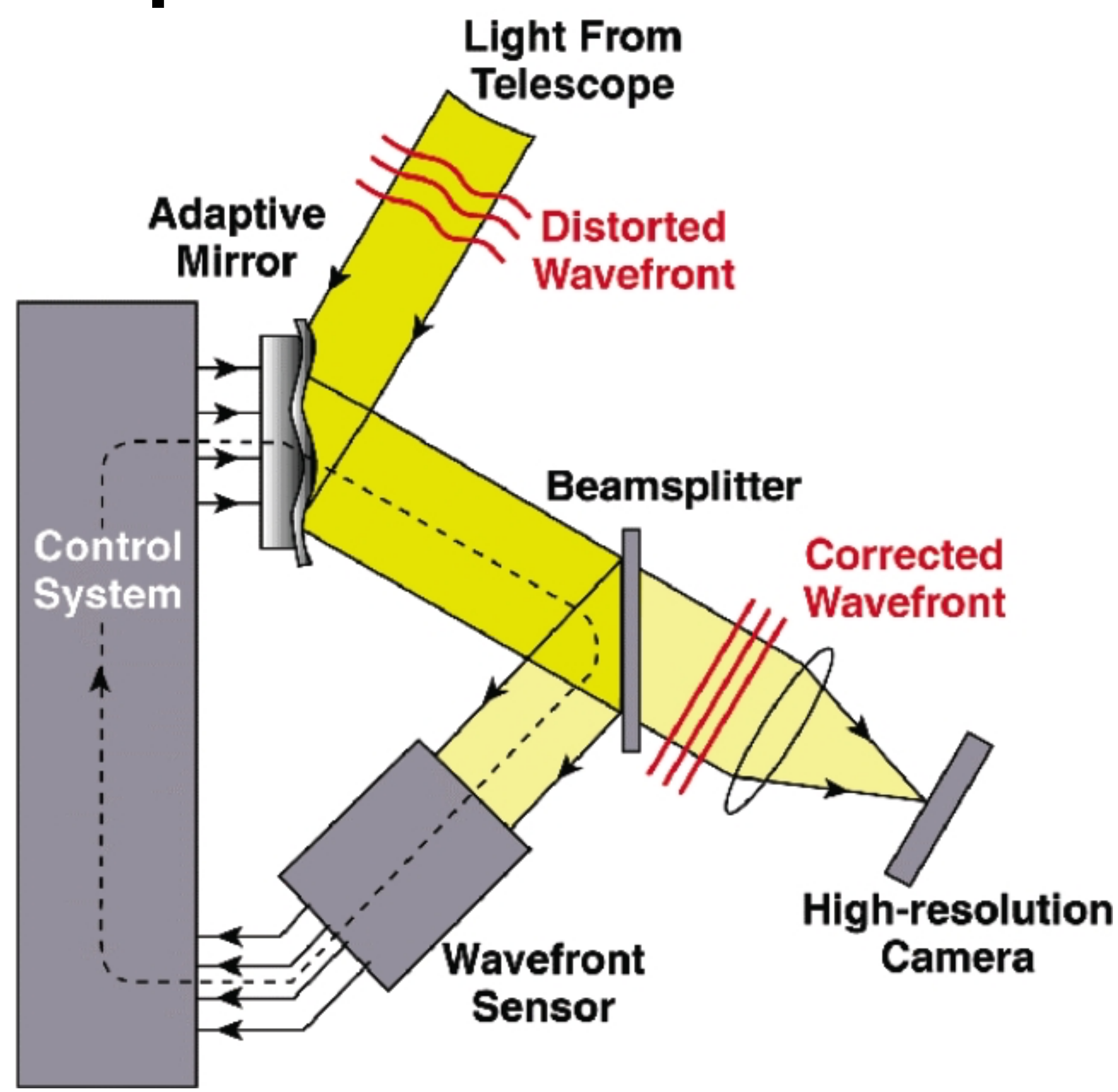


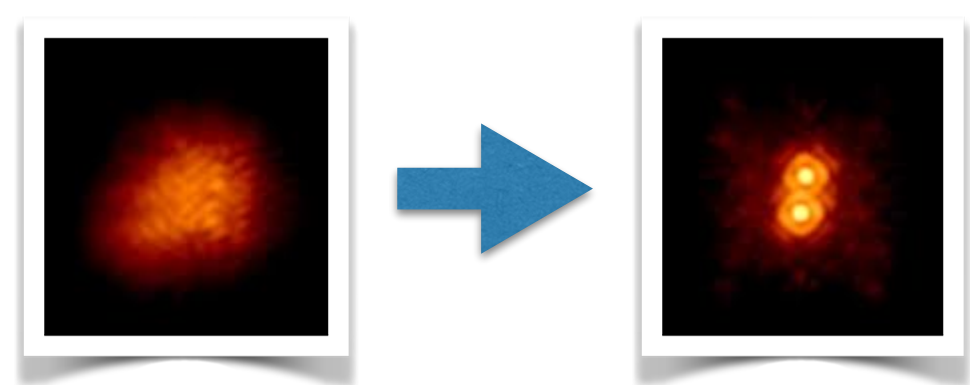
long exposure image

theoretical telescope PSF

Adaptive optics

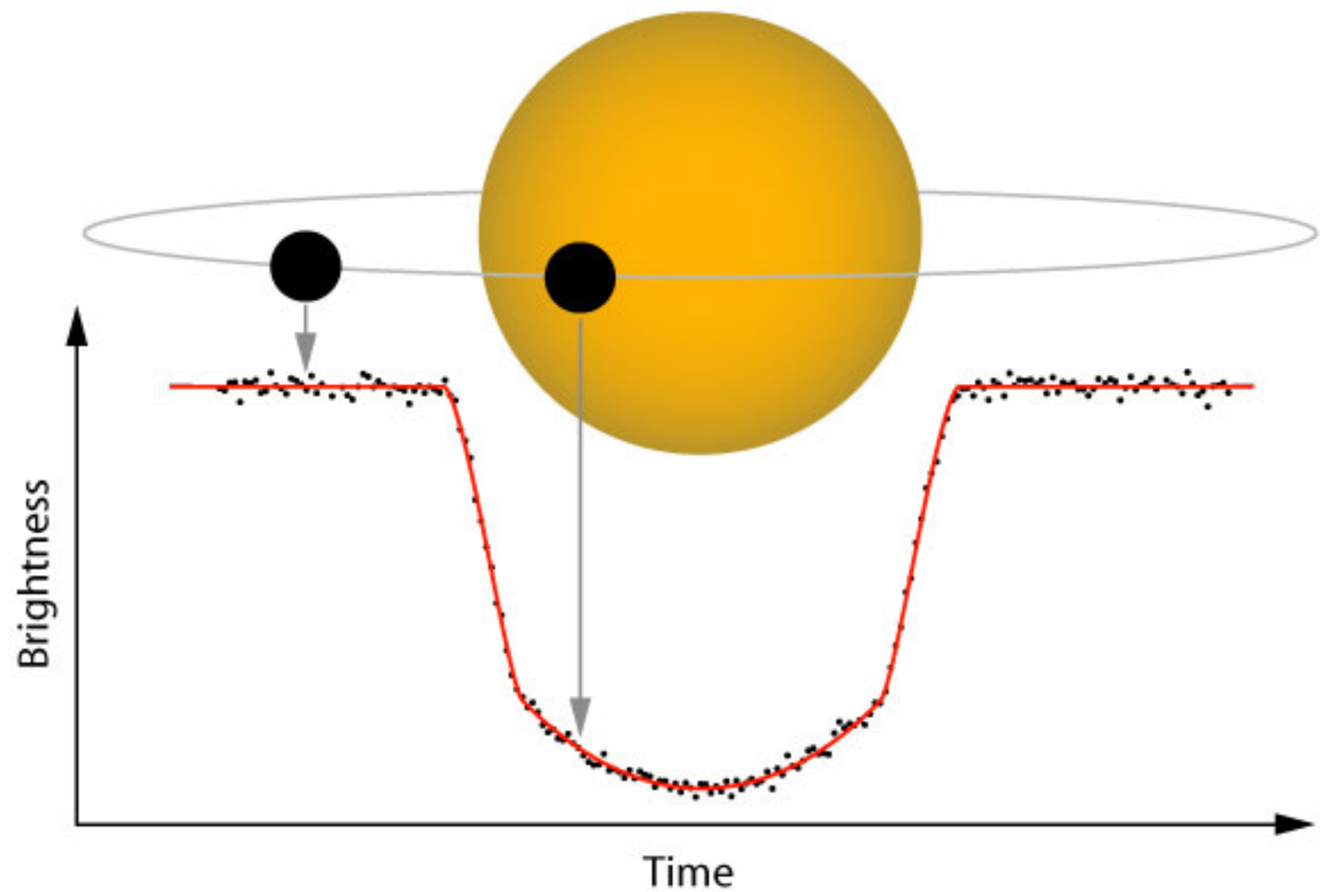
- Real-time wave front correction
  - wave front sensor
  - high-frequency deformable mirror (> 100 Hz)
- Correction is never complete
- Best solution: go to space!





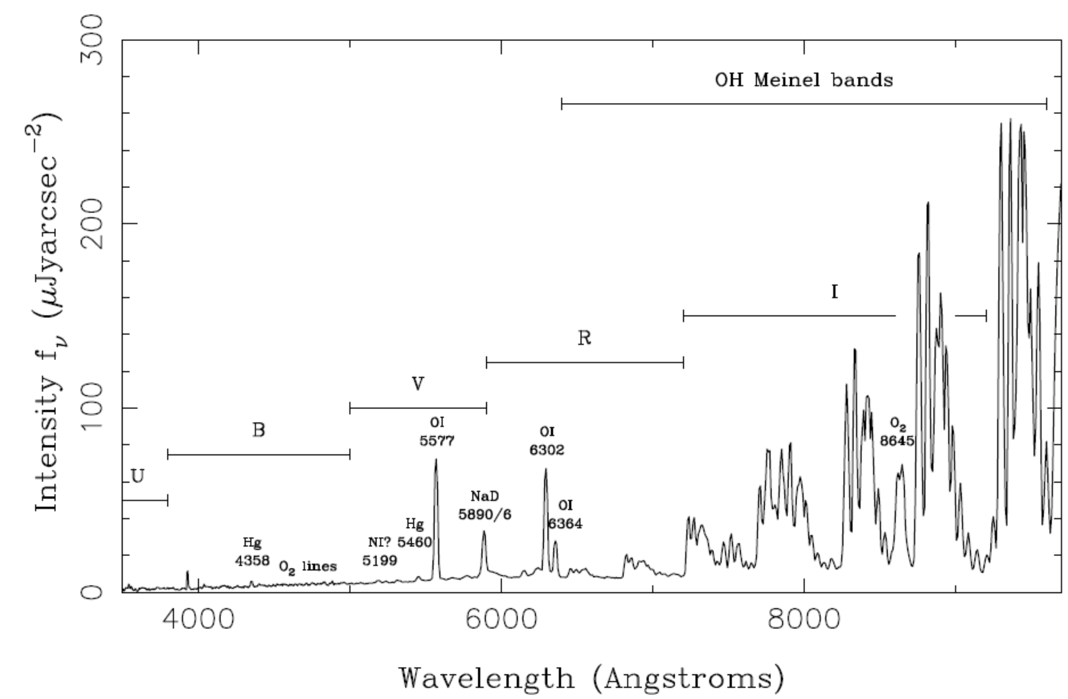
Stability / accuracy

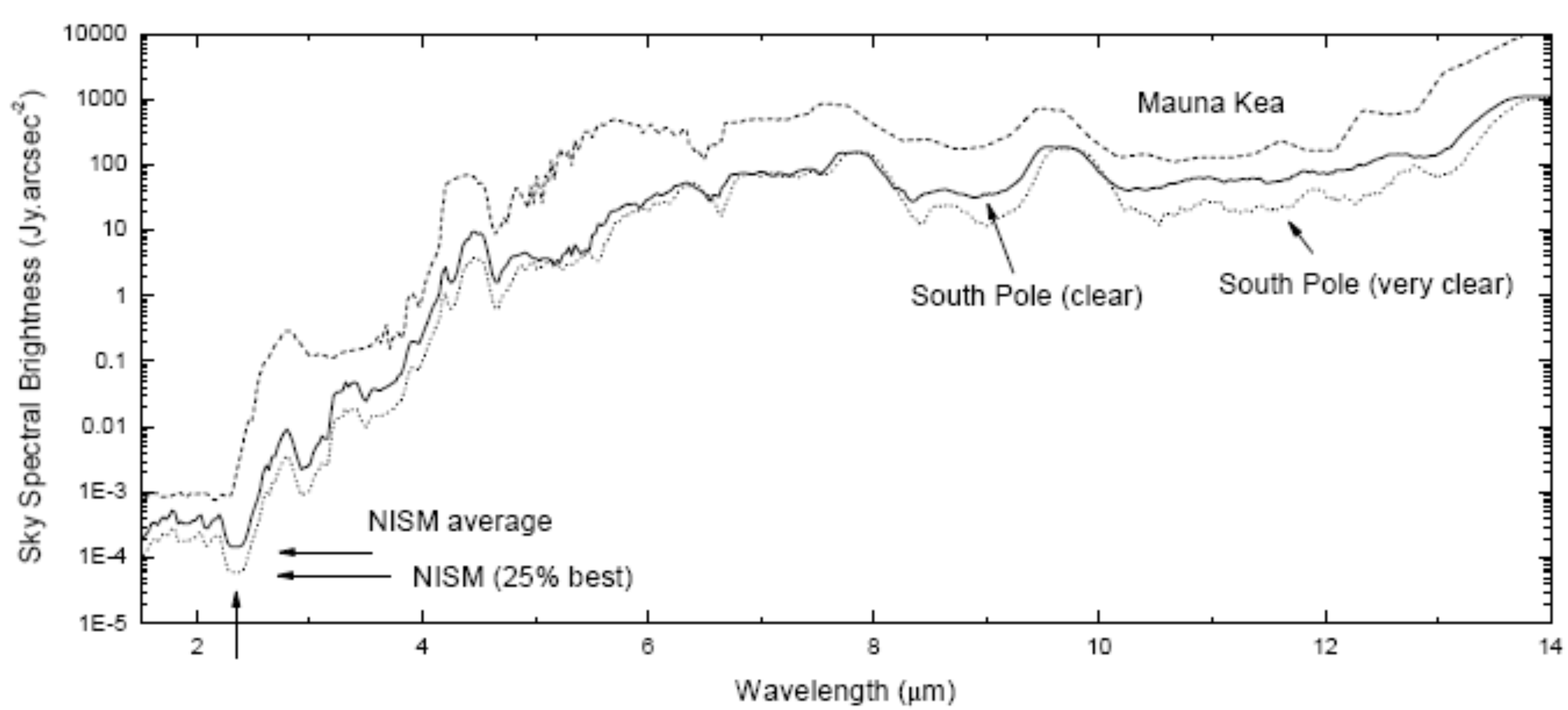
- Ground: scintillation, refraction, variability of the atmospheric transmission, etc.
- Space: enables high precision photometry



Sky emission / thermal background

- Visible range: airglow
- Infrared range: blackbody emission at 280 K (emissivity = 1 – transmission)



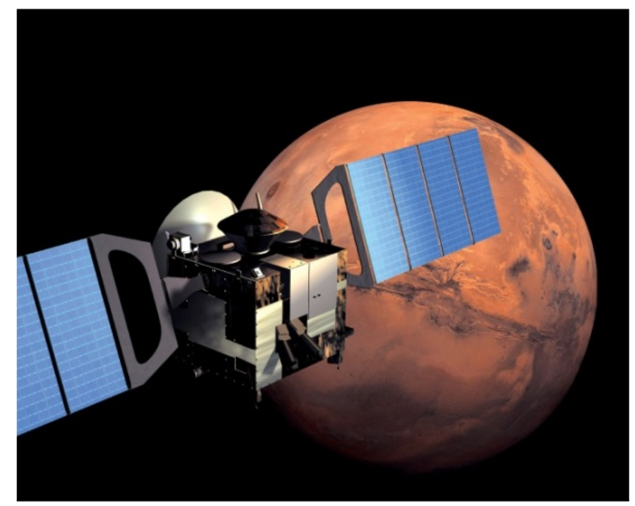


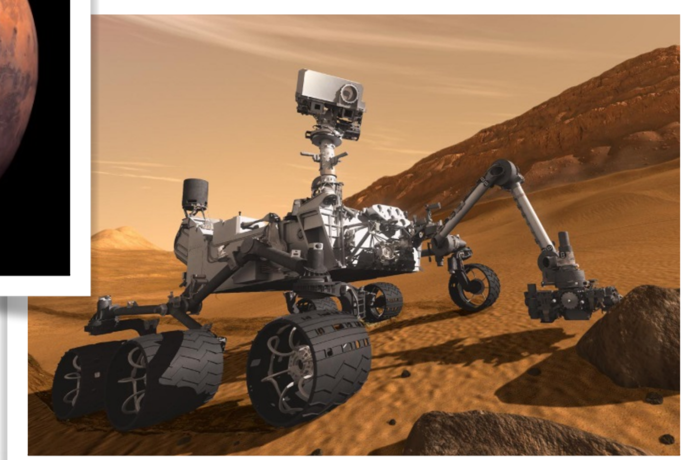
Summary: why space observatories?

- ✦ Access to full spectrum —> new phenomena
- ✦ Sensitivity —> see fainter, farther, younger
- ✦ Resolving power —> more details
- ✦ Stability (thermal, mechanical) —> more accuracy
- ✦ And more:
  - cooling of the optics
  - no night/day cycle —> long observations

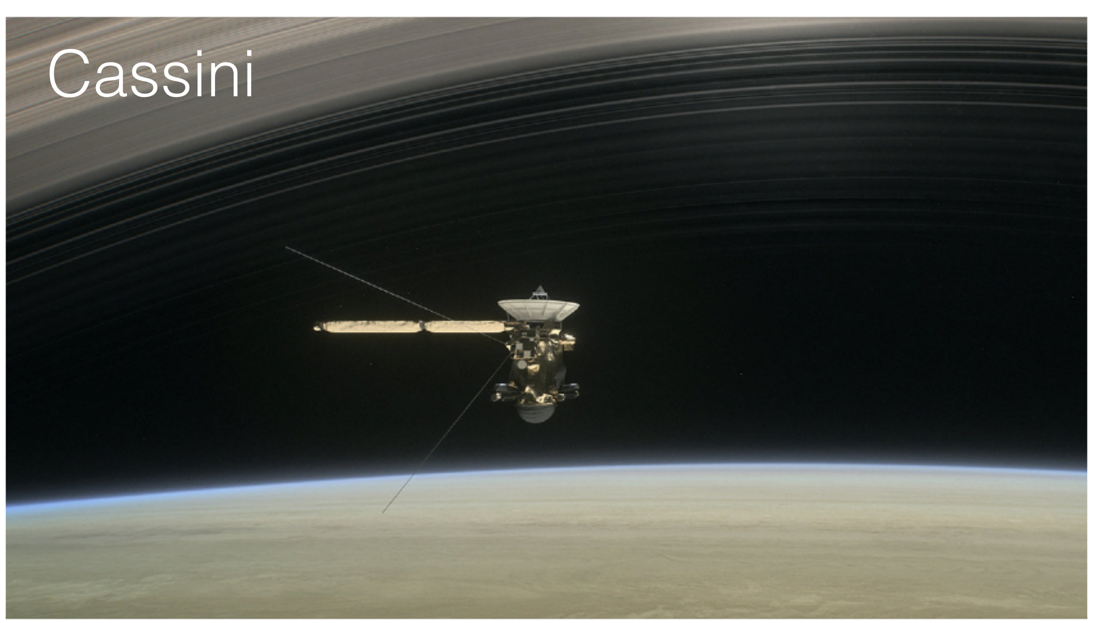
But also: in-situ exploration

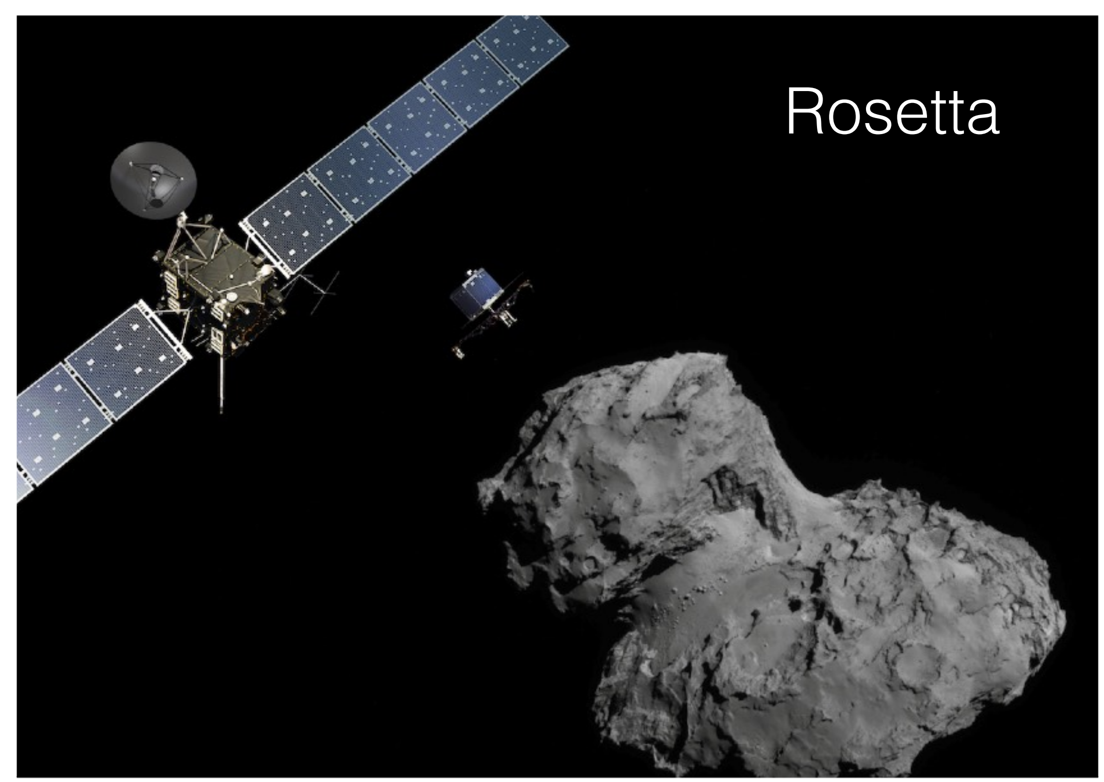
- ✦ Space rendez-vous
- ✦ Planetary orbiters
  - detailed cartography (3D)
  - magnetic field, …
- ✦ In-situ measurements (lander)





Mars Express, Curiosity, Perseverance, etc

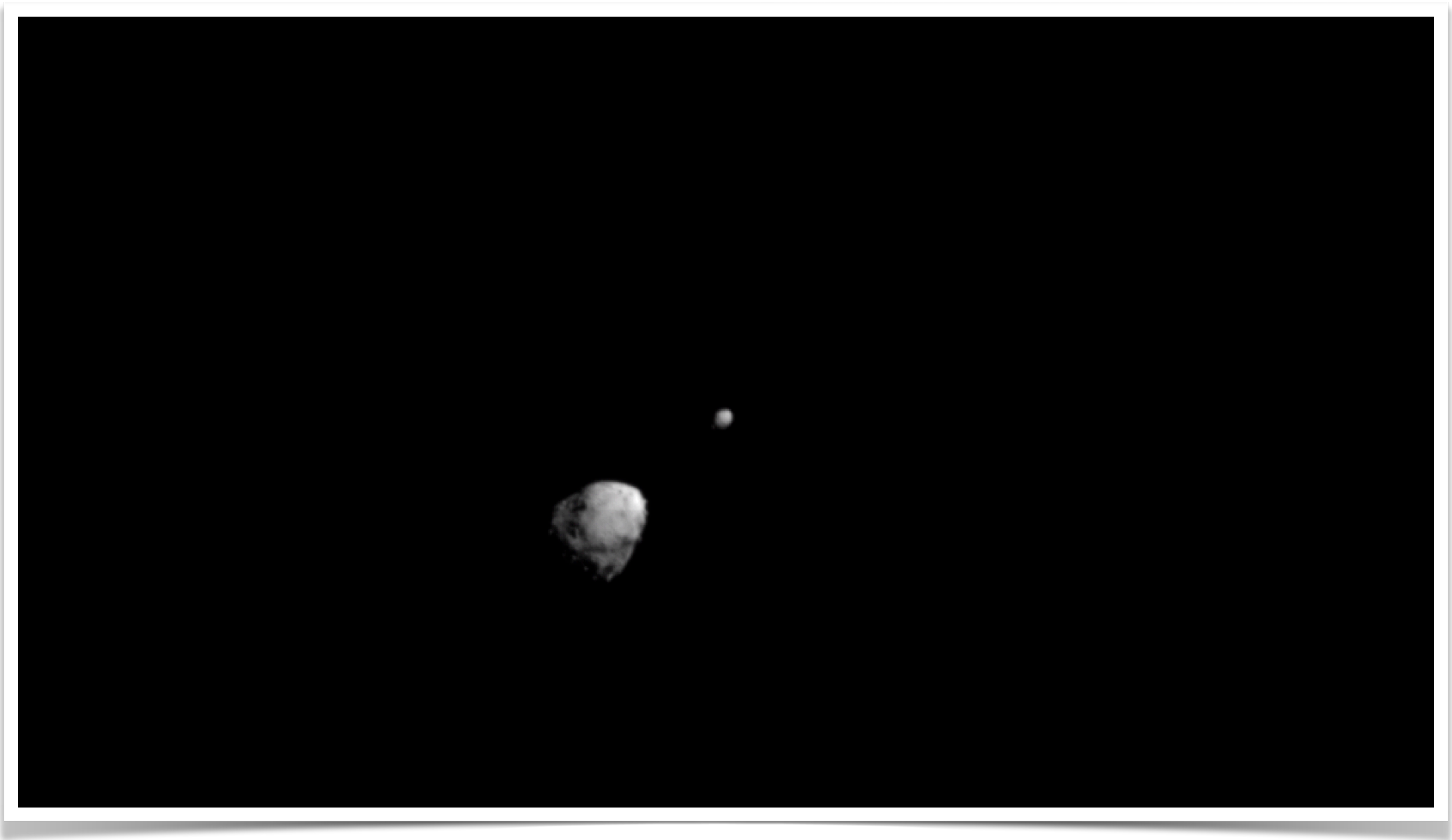




Collecting asteroid samples

60g collected during touch-and-go (Oct'20)

Preventing Armageddon…
(and learning more about asteroids)



DART mission hitting asteroid moonlet Dimorphos on Sep 26, 2022

Outline of the lecture

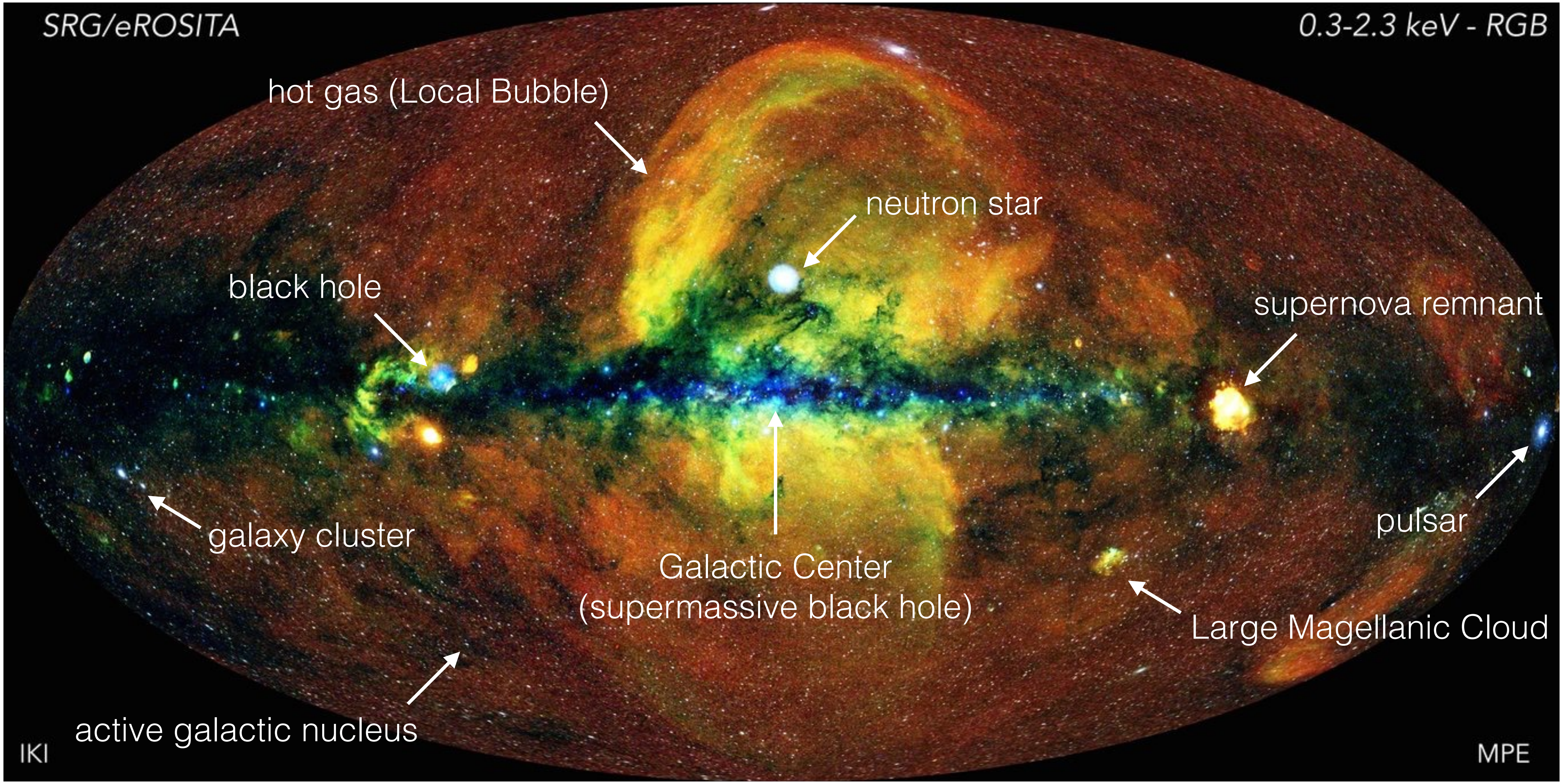
Lecture focused on **remote** observations:

1. X rays (0.1 nm —> 10 nm)
2. Visible / near infrared (300 nm —> 3 μm)
3. Mid-infrared (3 μm —> 30 μm)
4. Far-IR / submm / millimetric (30 μm —> 3 mm)

✦ Cosmic Vision: ESA's scientific program

Structure of each section

- Main interests of the wavelength range
- Example(s) of space mission(s)
- Technical challenges
- Some scientific results
- Future missions

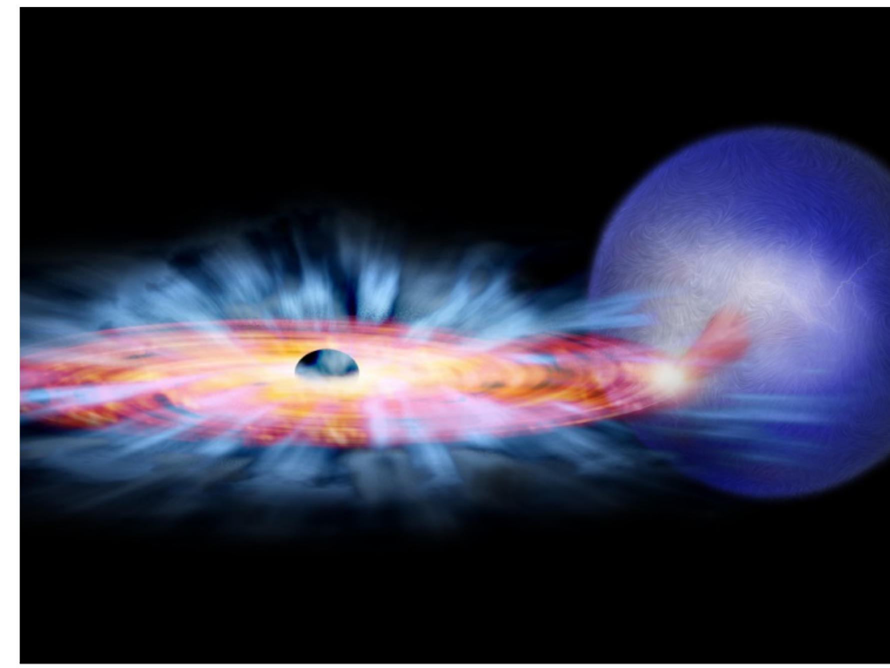


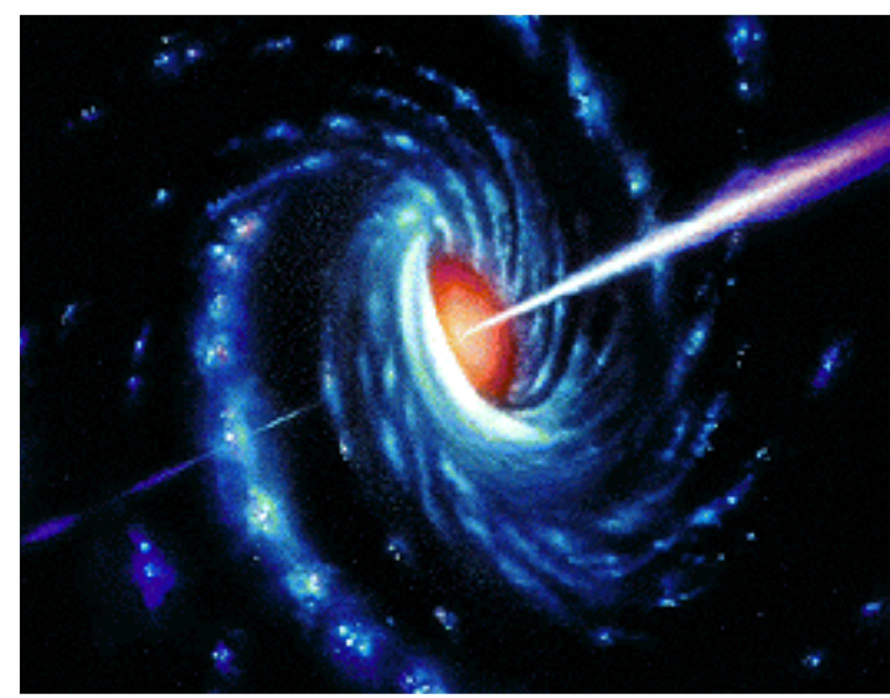
X-rays

From λ = 0.1 nm to λ = 10 nm

Astrophysical interests

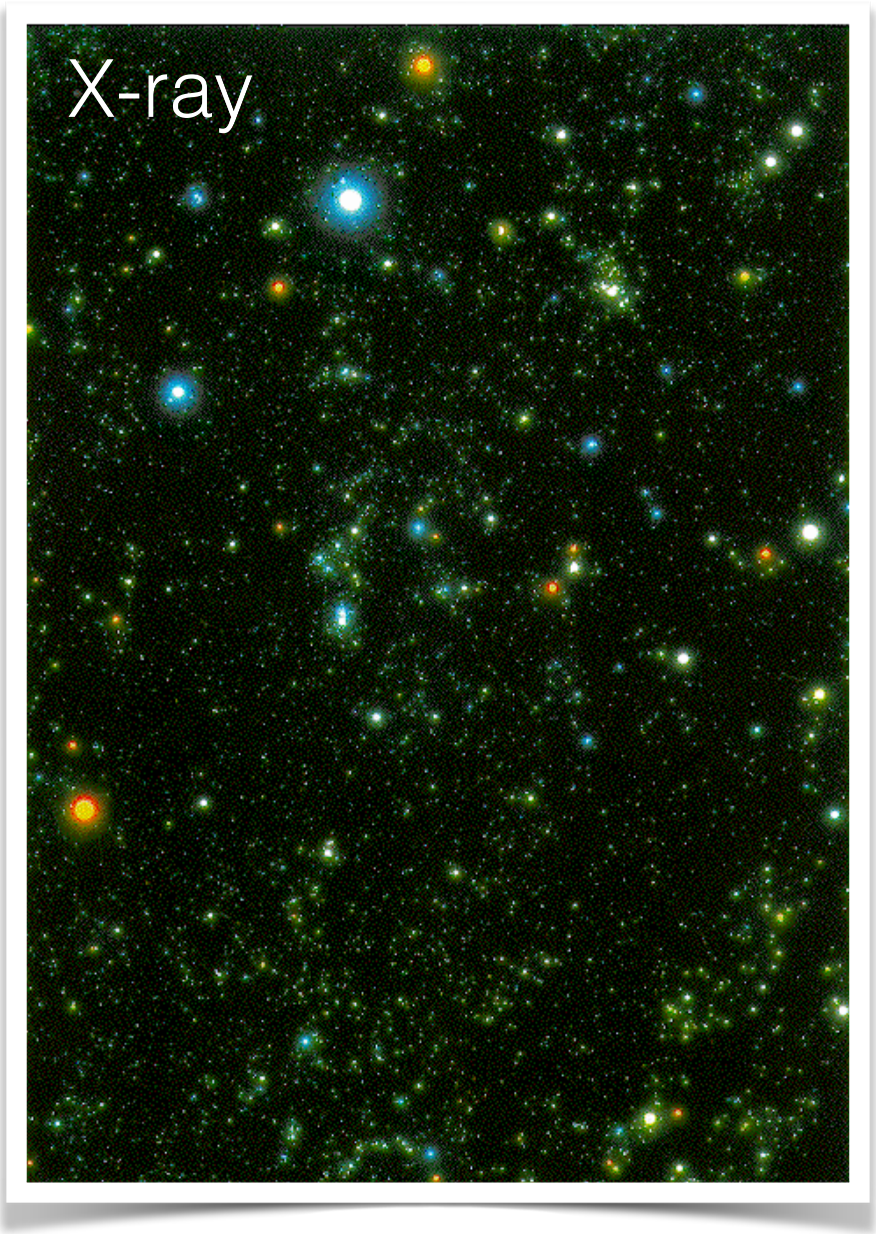
- Origin: hot gas, relativistic particles
  - stellar physics
  - X-ray binary = donor + accretor (neutron star, black hole)
  - quasars / active galactic nuclei
  - dark matter
- Violent phenomena





Astrophysical interests

- Another view on the Universe



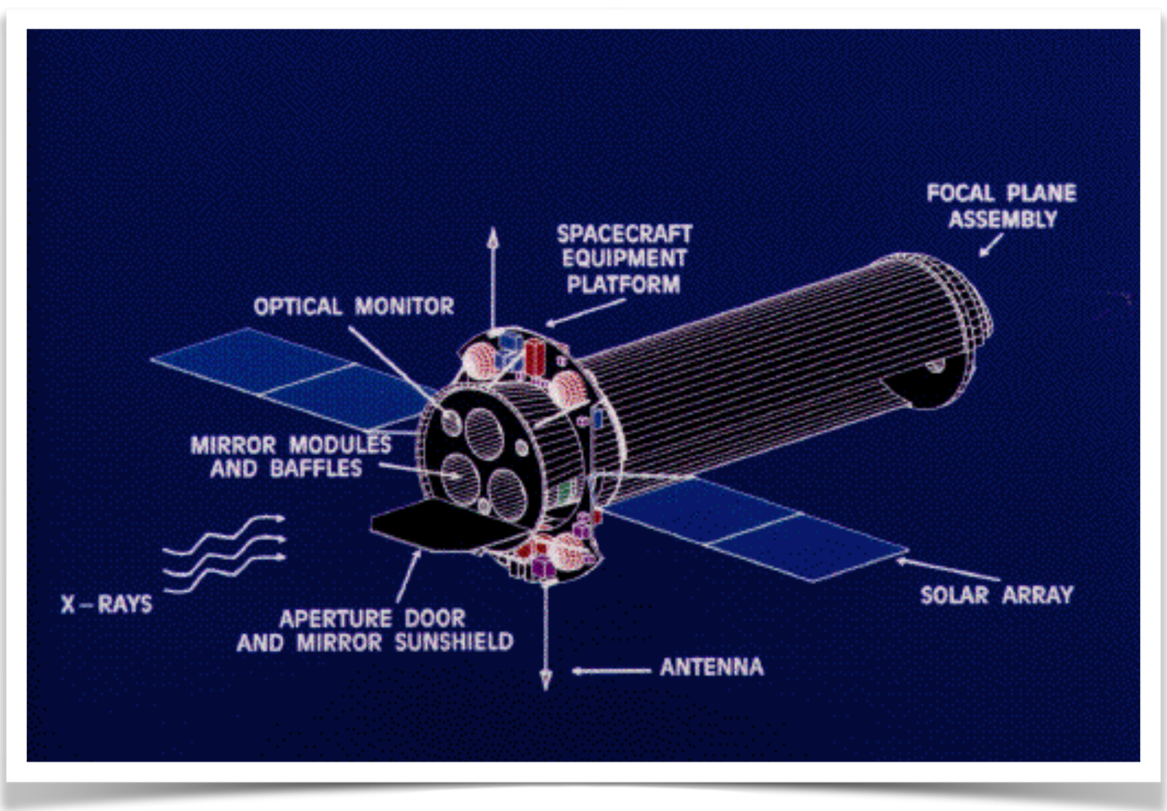
Two major missions (both still operating)

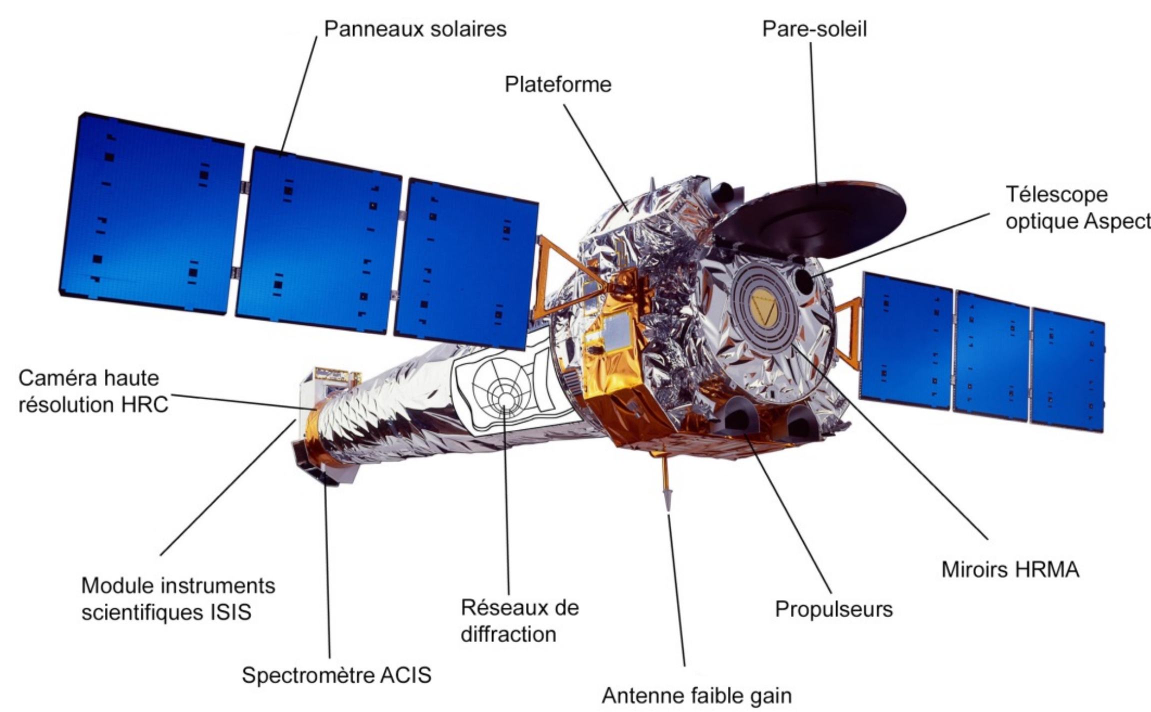
✦ XMM-Newton (1999)

- length: 10 m
- weight: 3.8 tons
- launch: Ariane 4

✦ Chandra (1999)

- length: 12 m
- weight: 1.5 tons
- launch: space shuttle

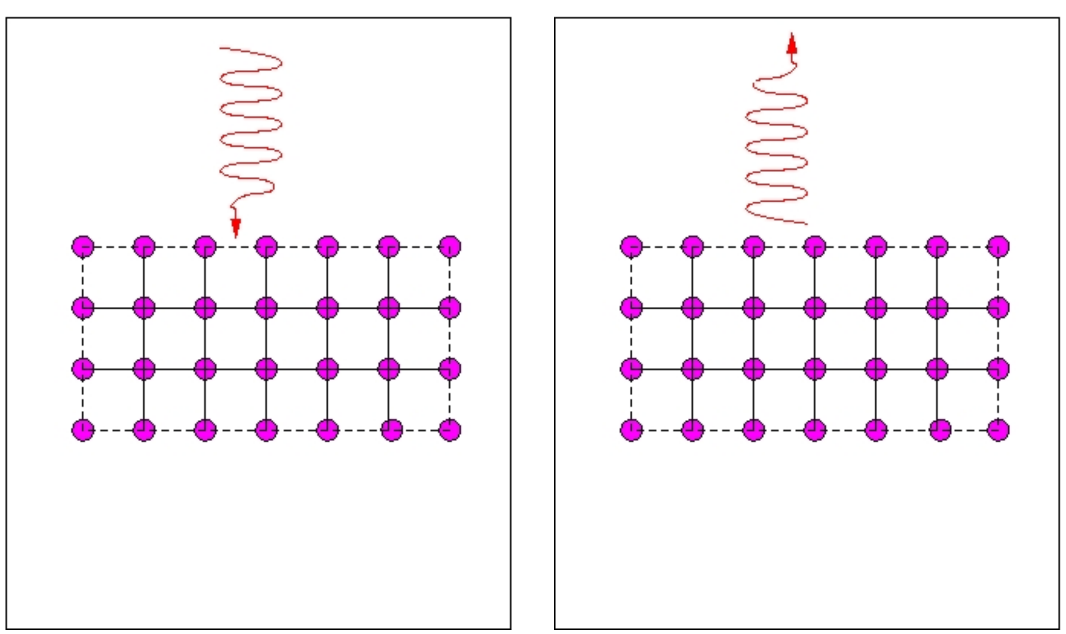




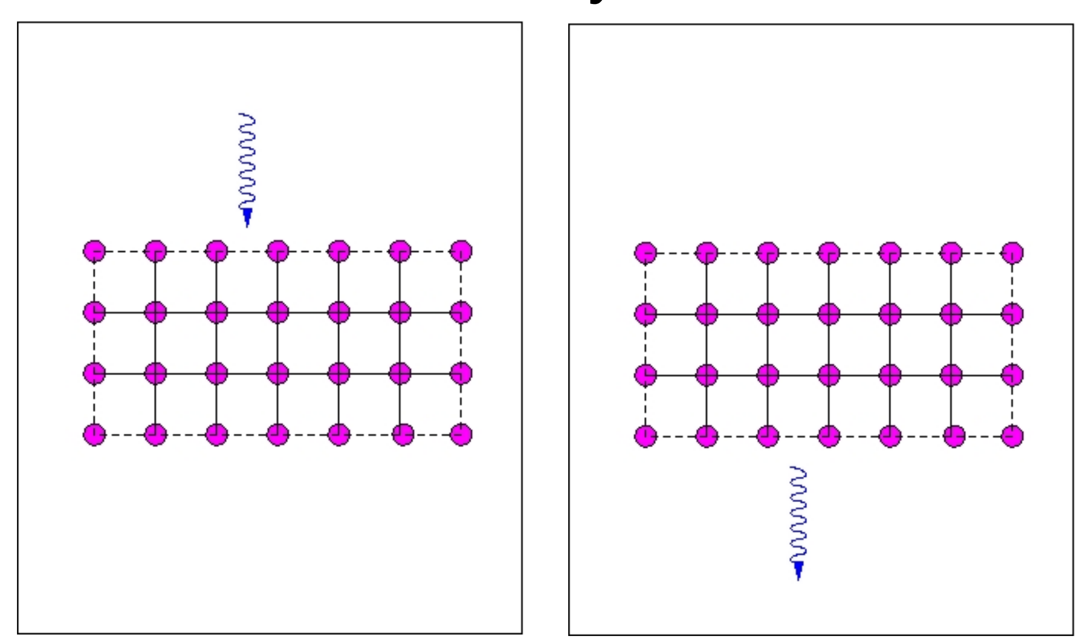
Focusing X rays

- ✦ A long story!
- ✦ X-rays —> high penetrating power
  - cannot be reflected off in normal incidence

Visible light

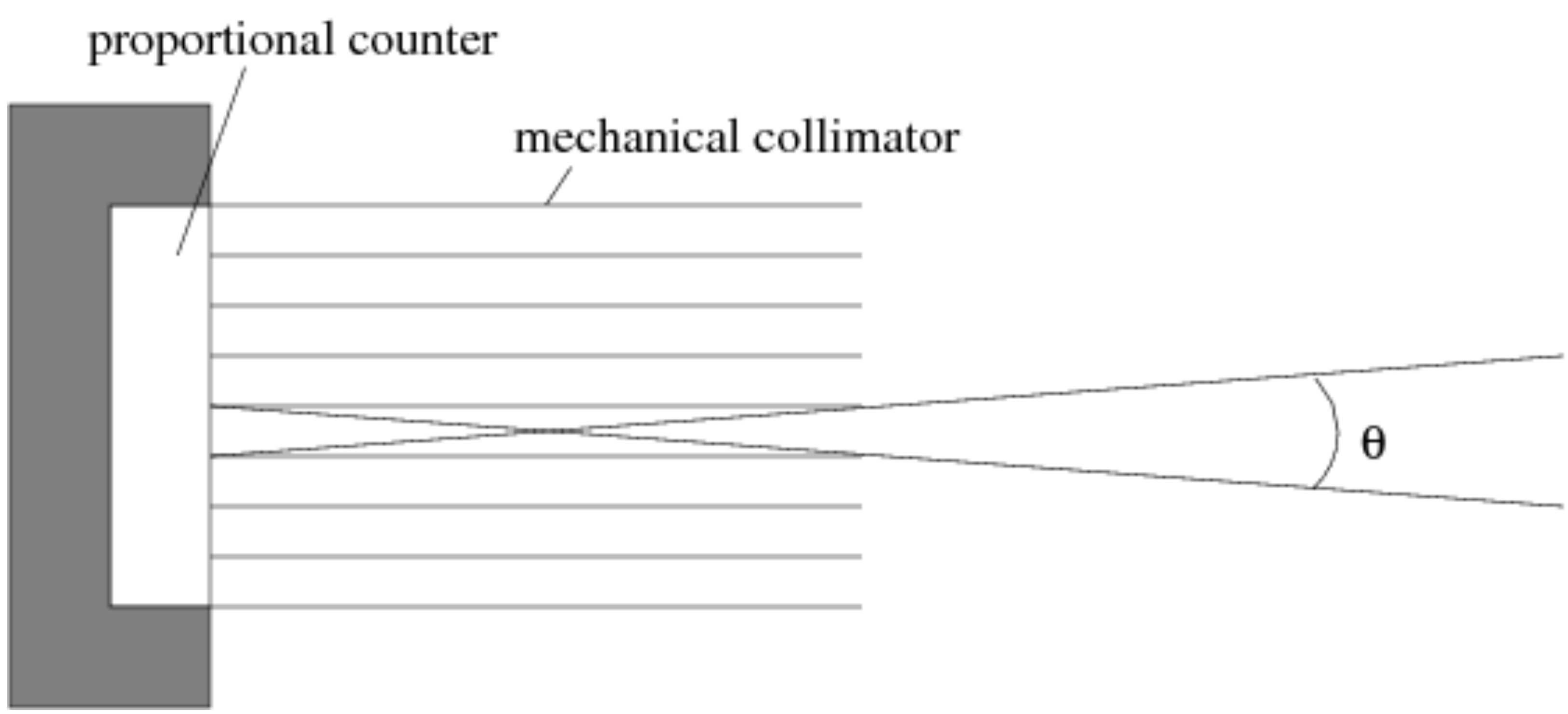


X rays



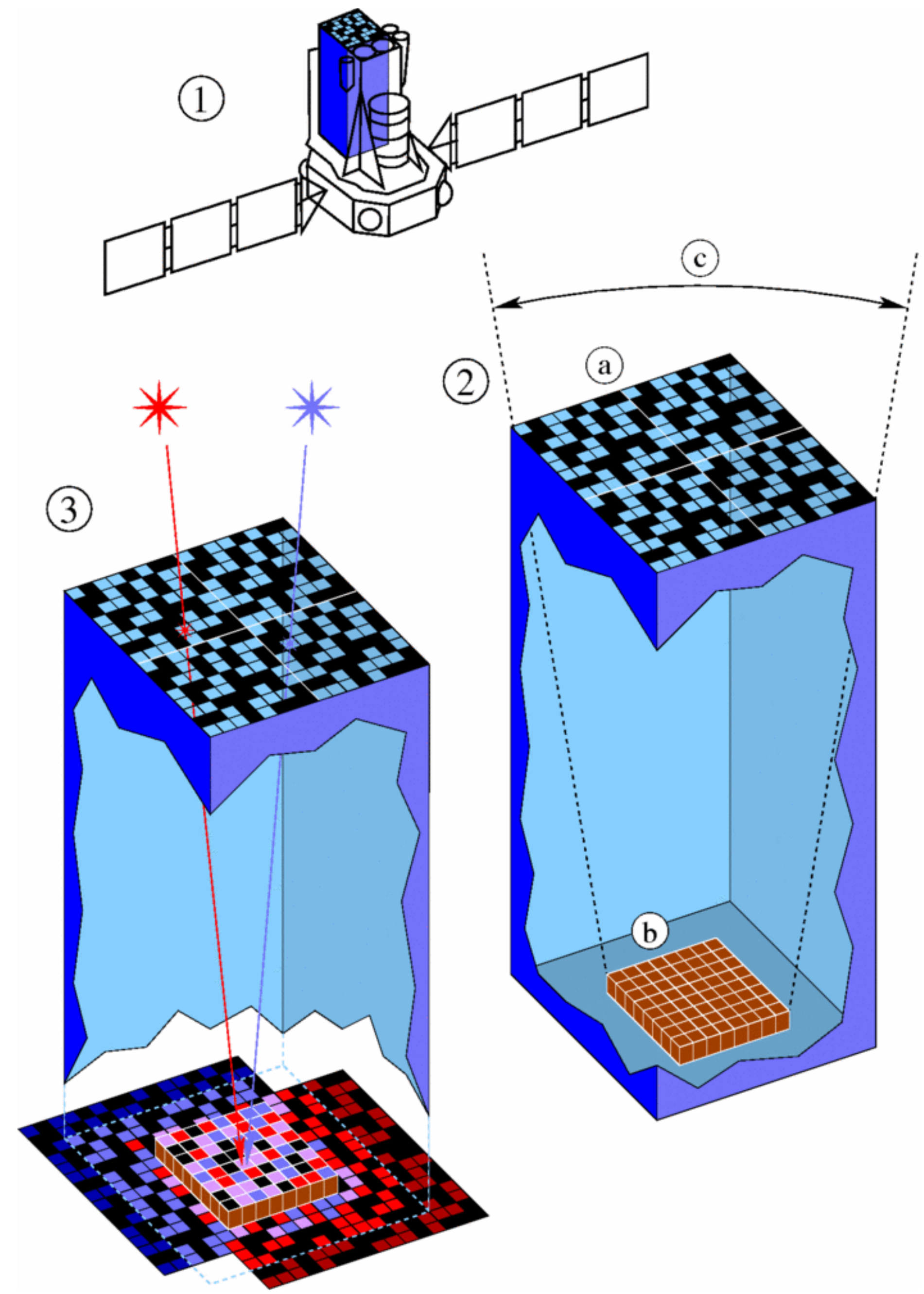
Focusing X rays

- First solution: mechanical collimator
  - set of hollow tubes in front of the detector to restrict the direction of light rays
- Does not give a true image (need to scan)



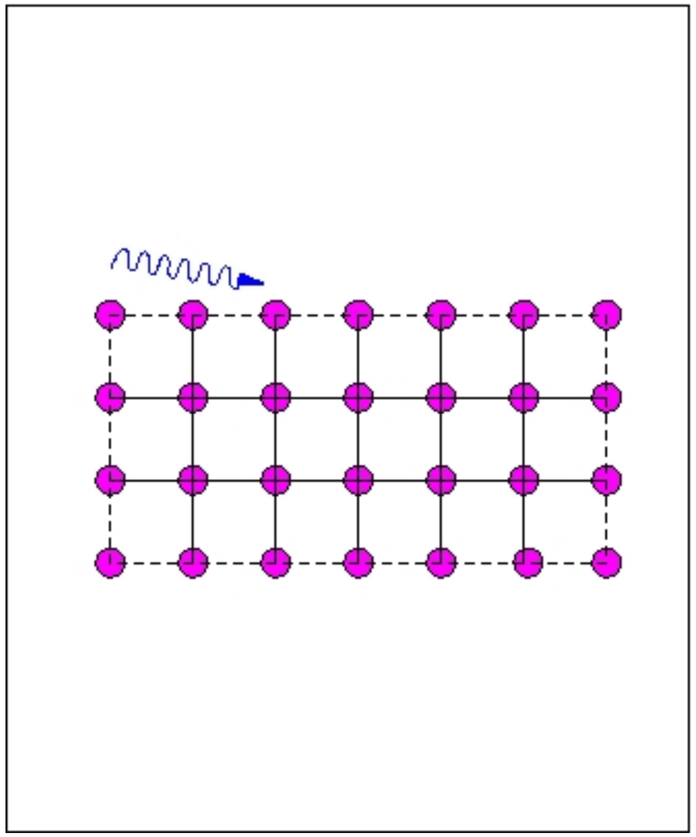
Focusing X rays

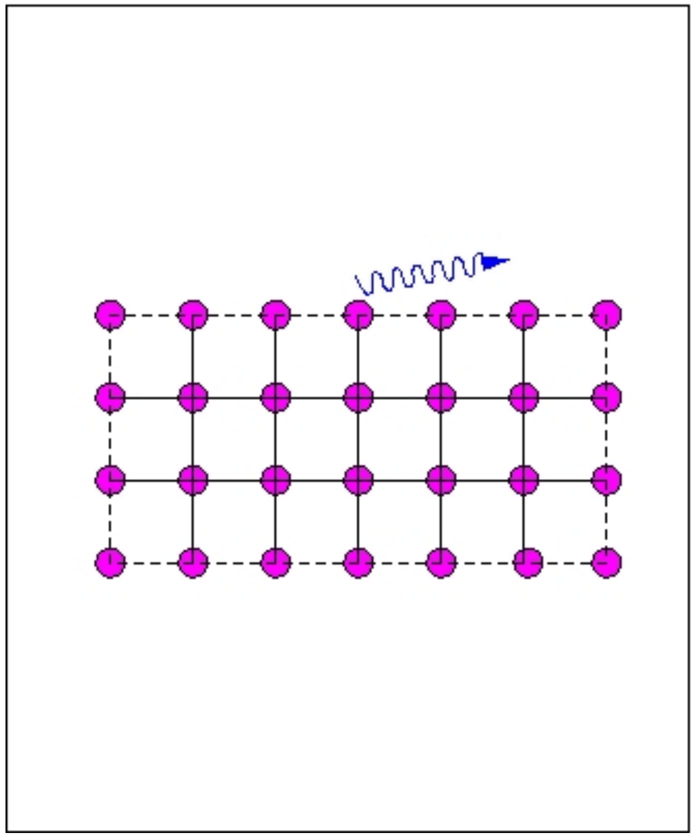
- ✦ Second solution: coded aperture
  - partial masking of telescope aperture
  - measure the superposition of mask shadow projected onto the detector
- ✦ Drawbacks
  - low resolving power
  - limited sensitivity (light spread on many pixels)
- ✦ Still used in ɣ-ray astronomy

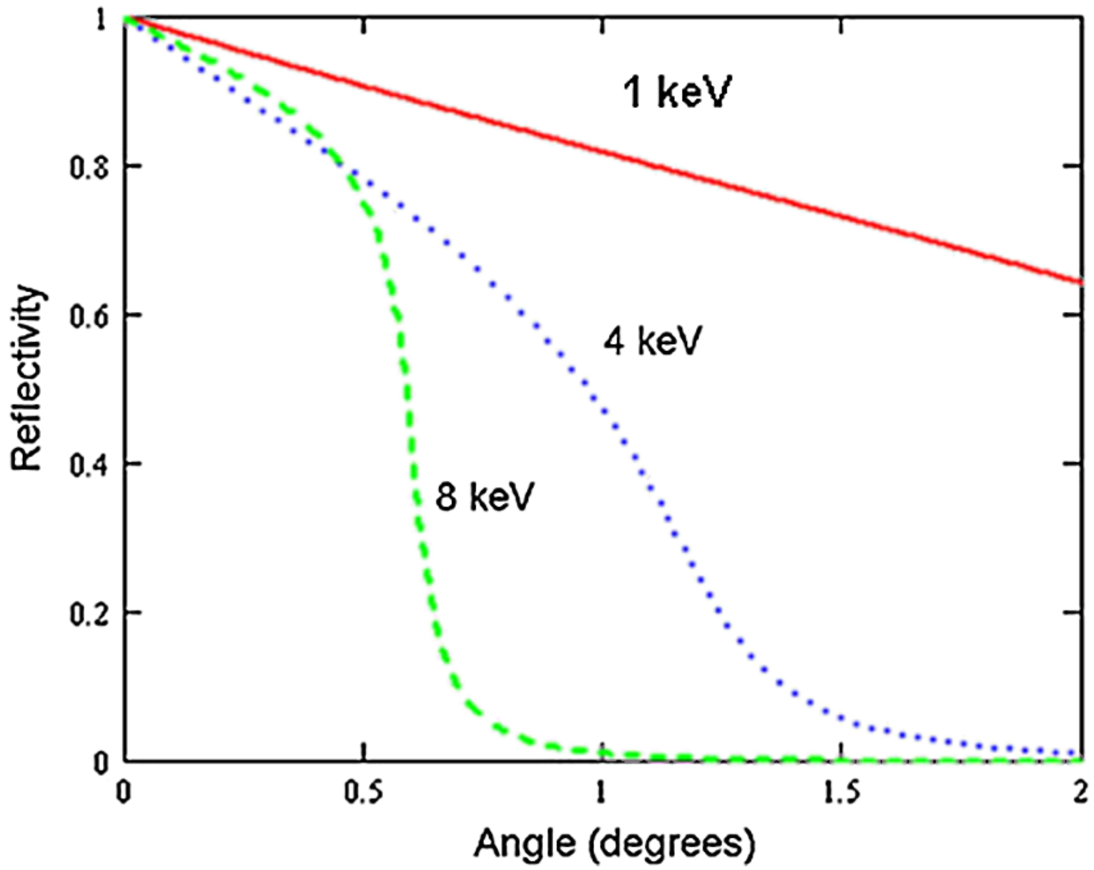


Focusing X rays

- Third solution: grazing incidence

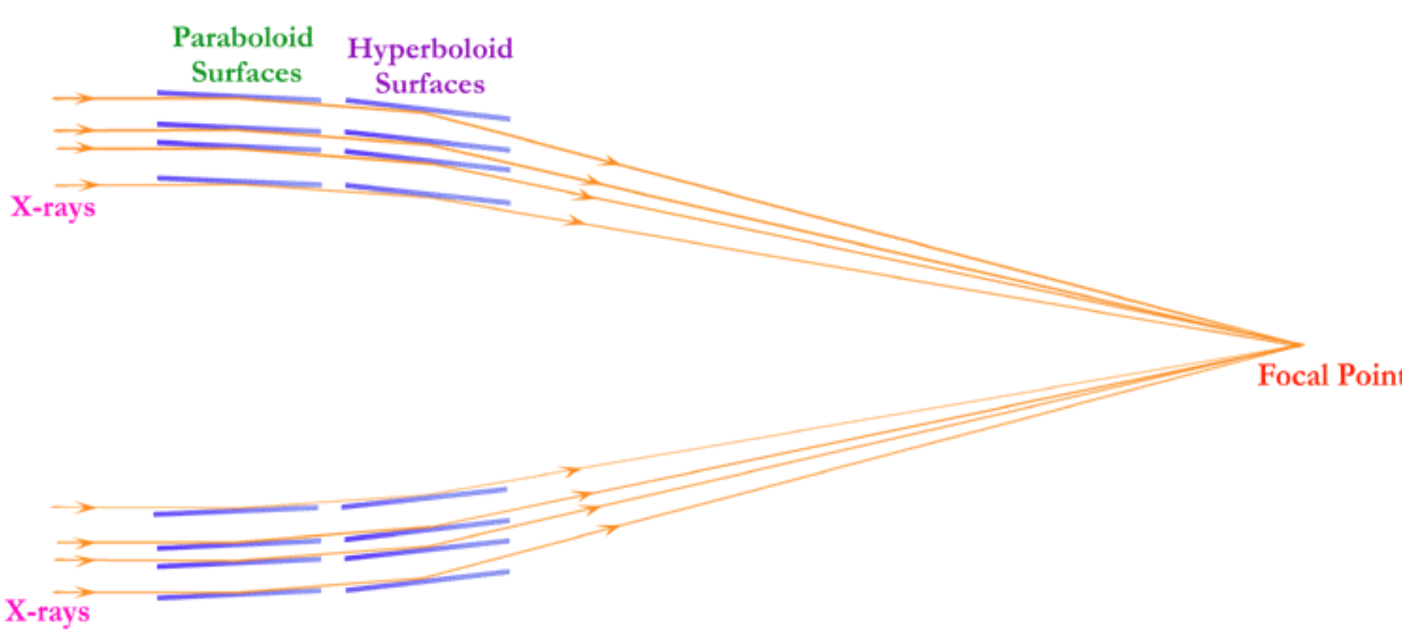


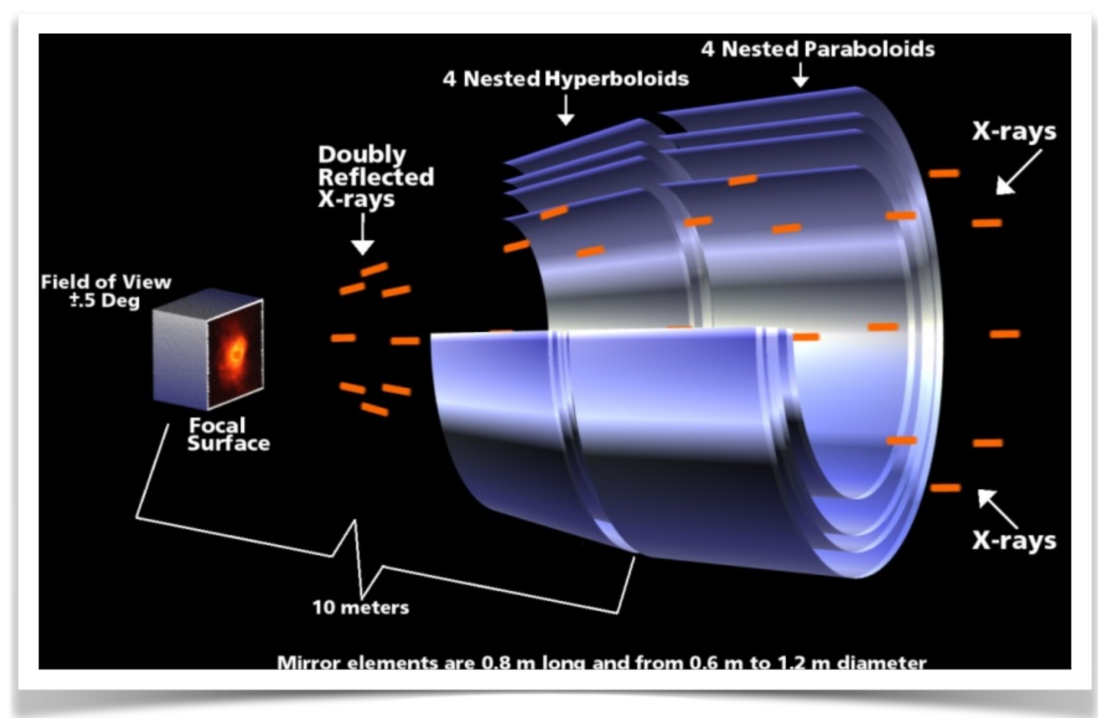




Focusing X rays

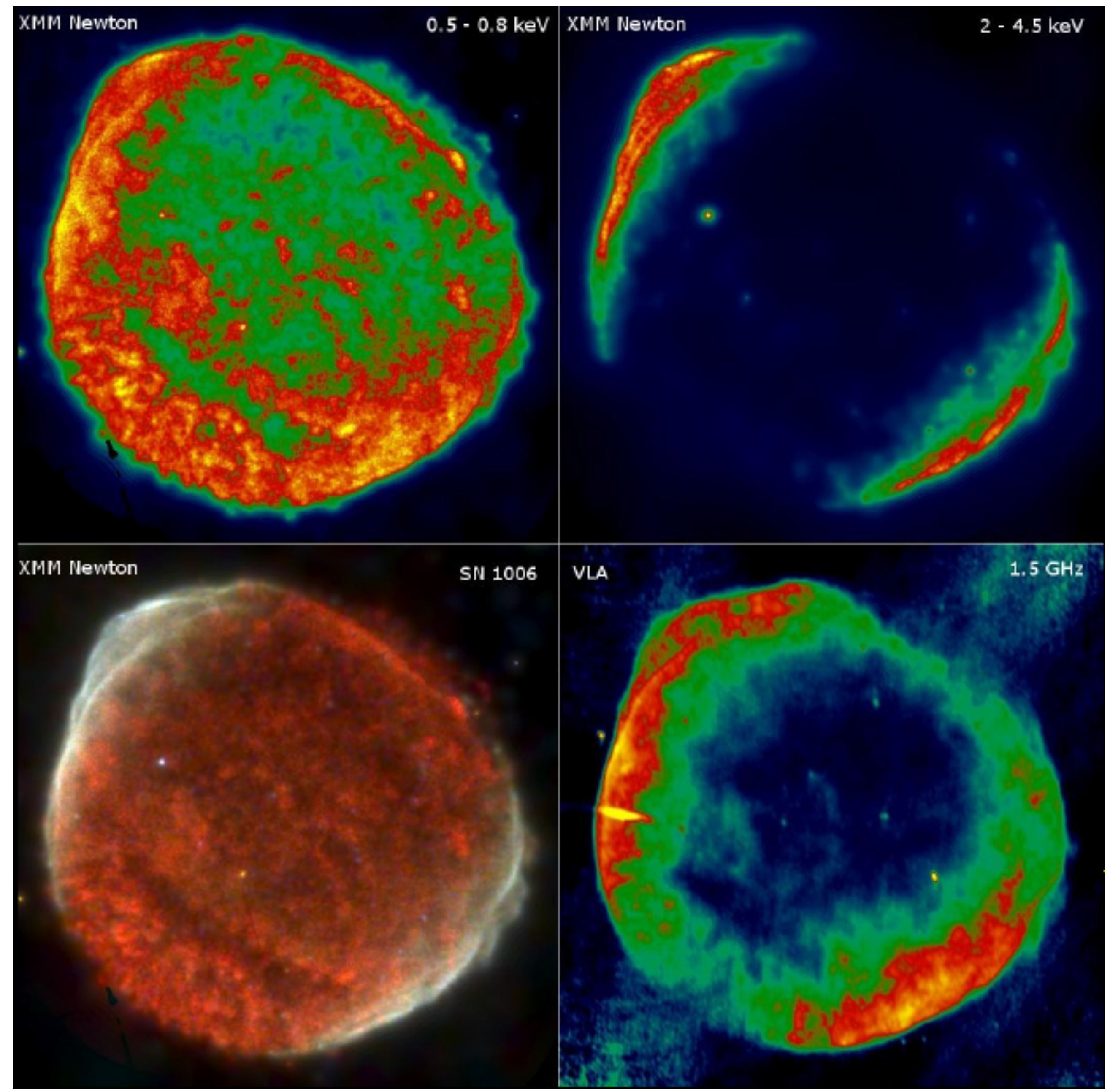
- Implementation of grazing incidence
  - true telescope, with very long focal length
  - Wolter-type design: combines two reflections (paraboloid and hyperboloid)
  - increase collecting area —> nested mirrors





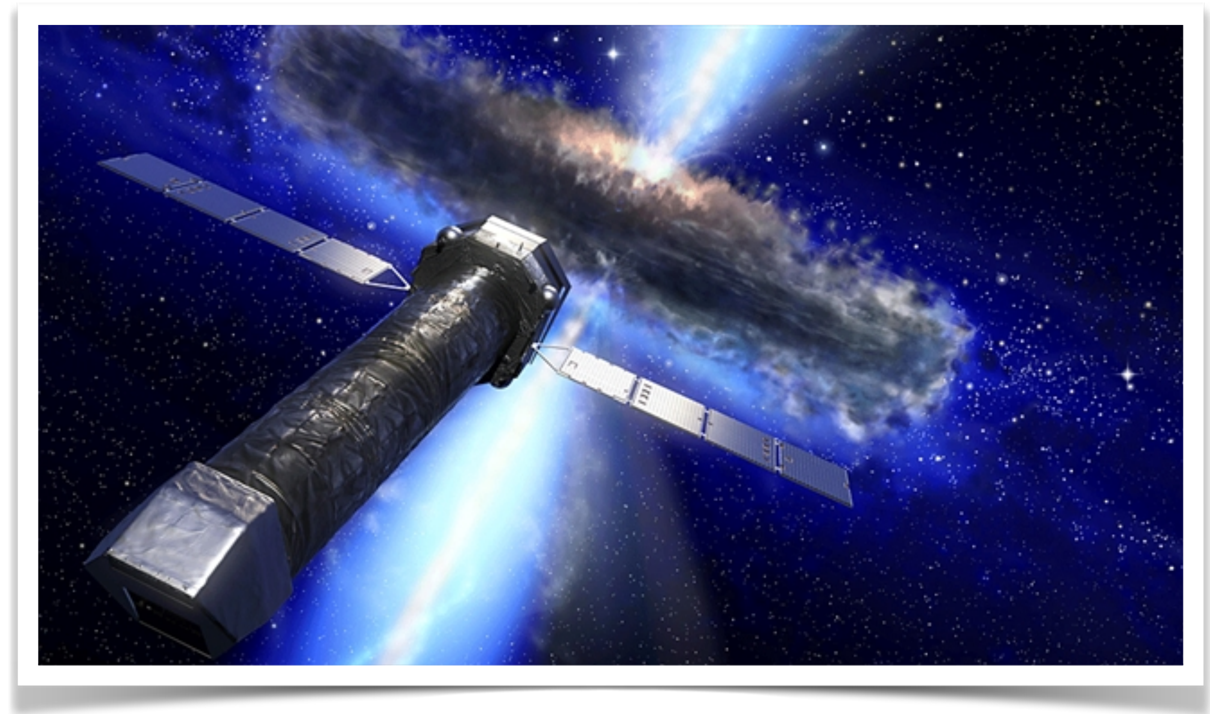
Major results

- ✦ Accretion/ejection phenomena
- ✦ Discovery of ultra-hot plasma (> 10^6 K)
- ✦ Supernovae: explosions and remnants
- ✦ Pulsars, magnetars, X-ray binaries, black holes, etc
- ✦ Highest energy: ɣ-ray bursts

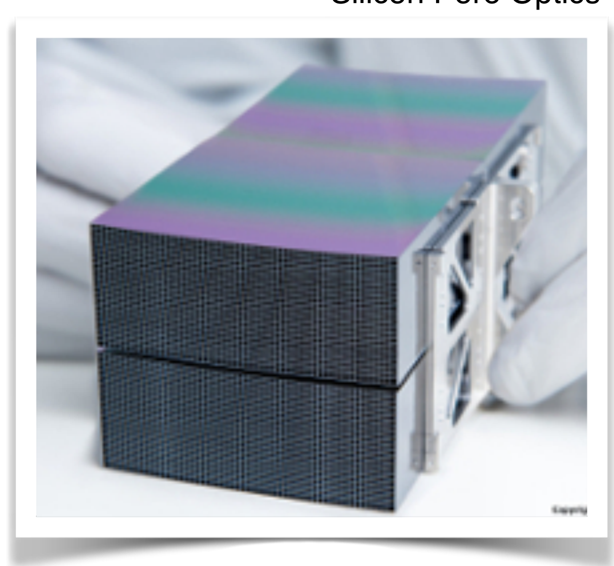


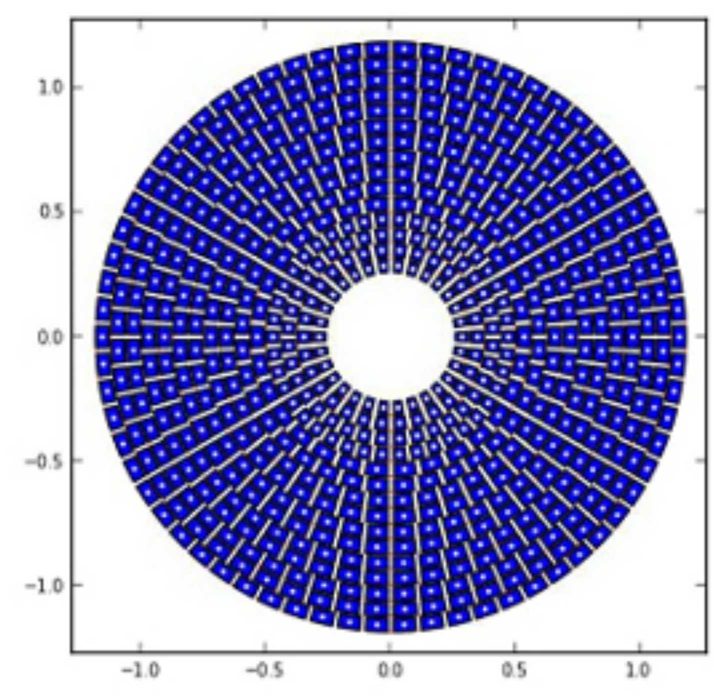
Future missions

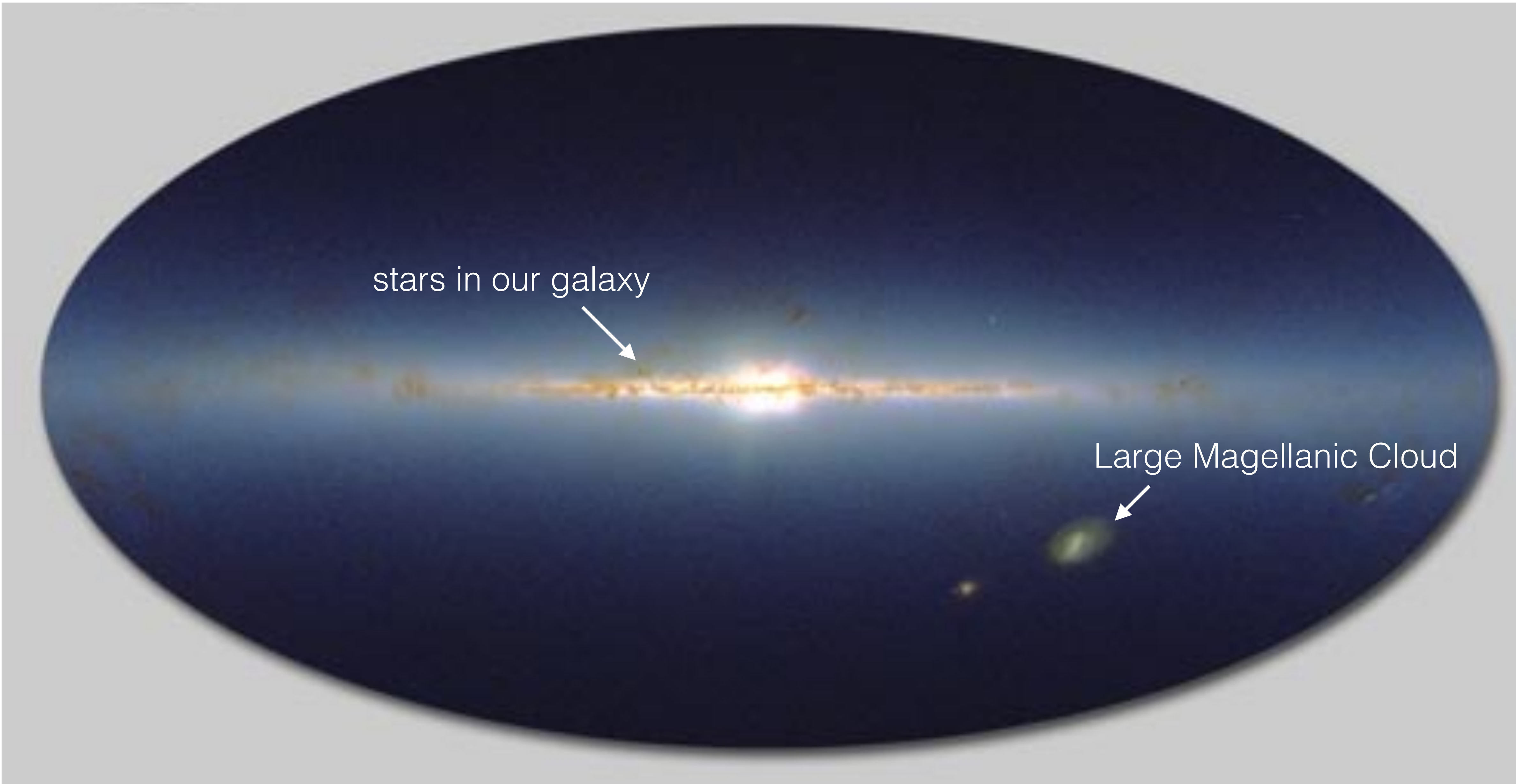
- ✦ Goal: increase collecting area
- ✦ ATHENA project (2035)
  - effective collecting area of 1.4 m^2 (3x more than XMM)
  - angular resolution: 5 arcsec
  - focal length: 11 m
  - mass < 6.5 tons
  - new lightweight technology
- ✦ To go beyond: deployable structures, formation flying



Silicon Pore Optics





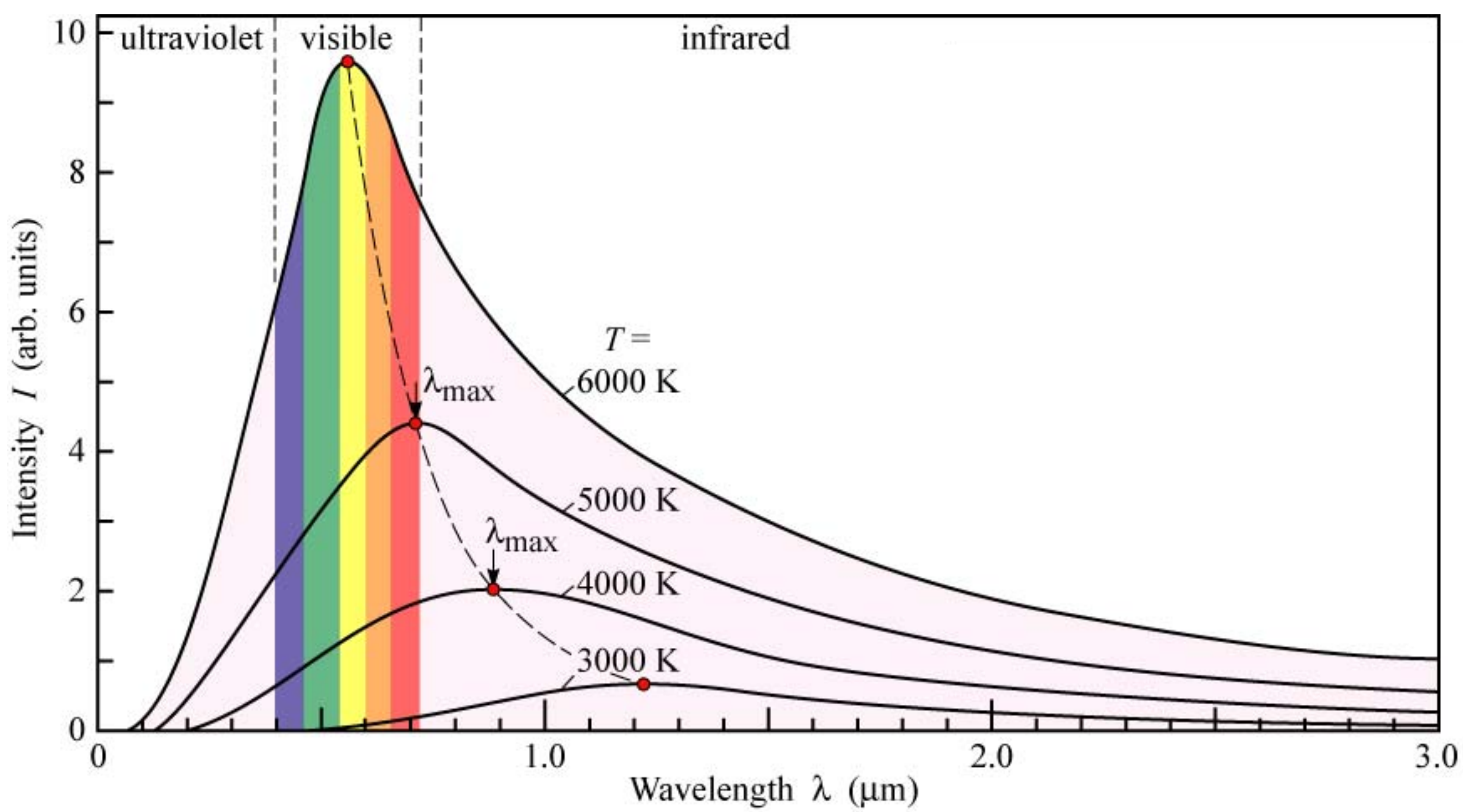


Visible / near-infrared

From λ = 300 nm to λ = 3 μm

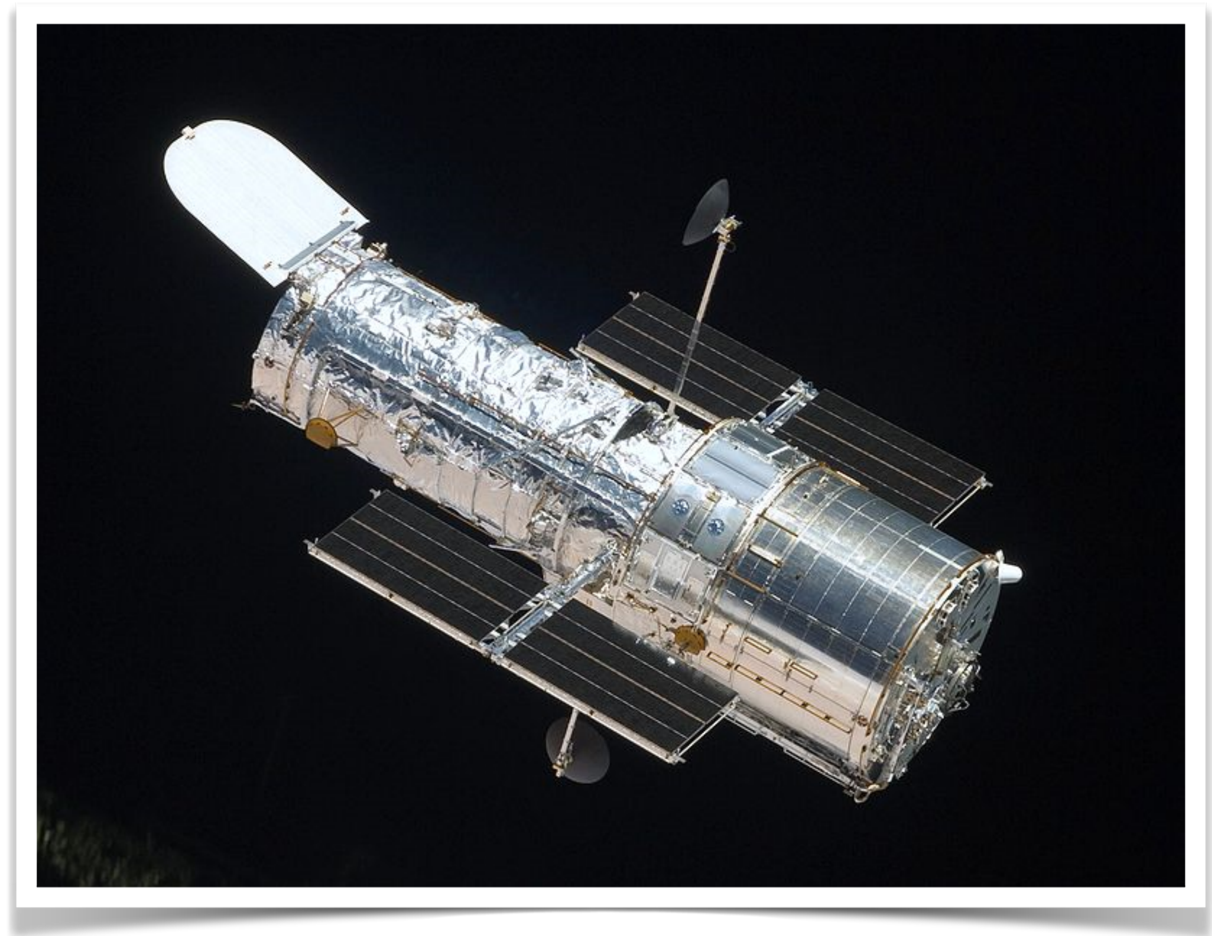
Astrophysical interests

- From Wien's law: λ_{max} (μm) = 2898 / T (K)
  - thermal emission at 3,000 - 10,000 K
  - realm of stars / galaxies



Hubble Space Telescope

- ✦ Idea born: 40's
- ✦ Project started: 60's
- ✦ Design / construction: 70's-80's
- ✦ Launch: 1990 (7 yr late)
  - space shuttle (Discovery)
  - low Earth orbit (560 km)
- ✦ Mission extended till 2026. Lifetime limited by failing gyroscopes and orbital decay (+ instruments aging).

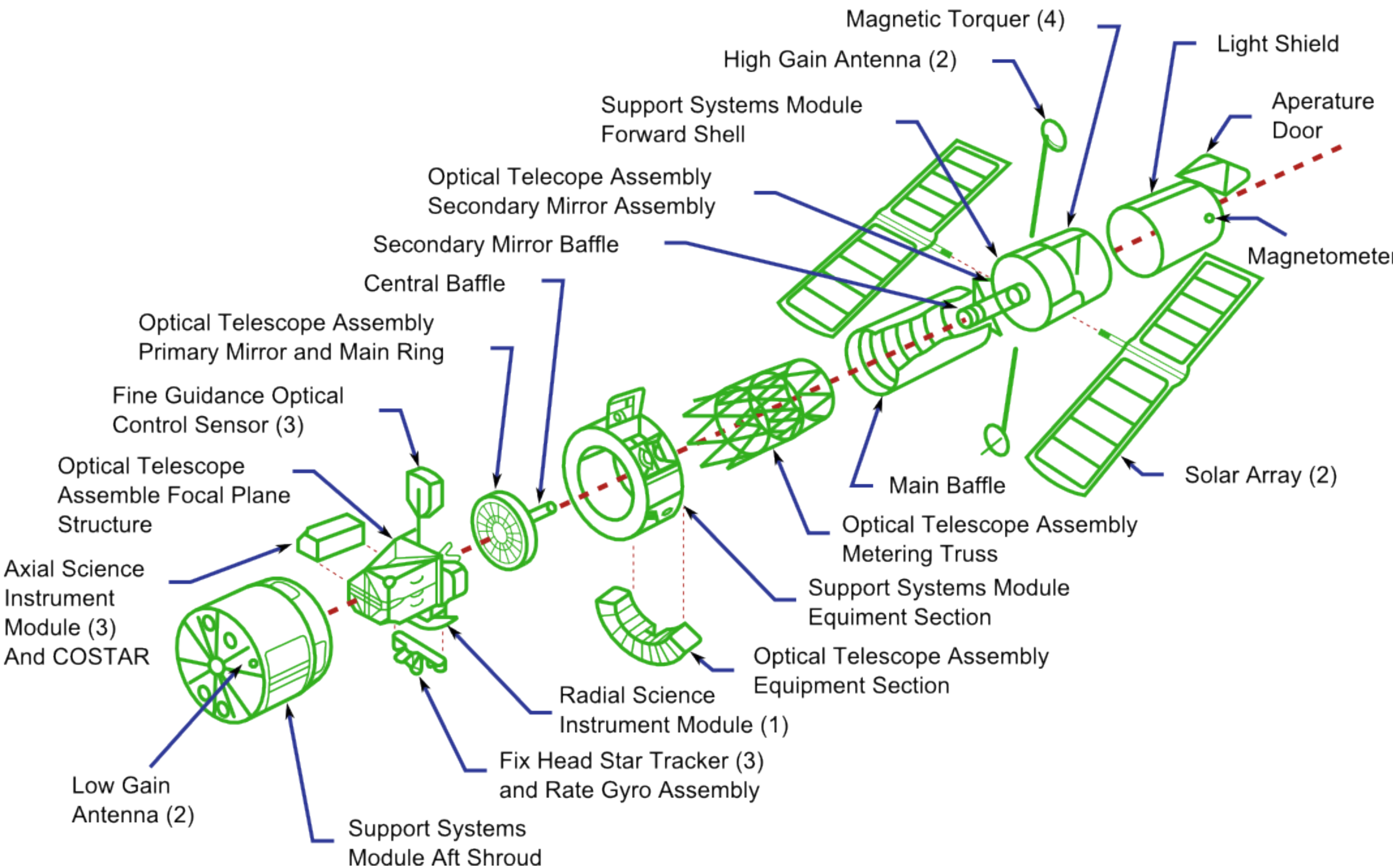


Length: 13 m
Weight: 11 tons

Hubble Space Telescope

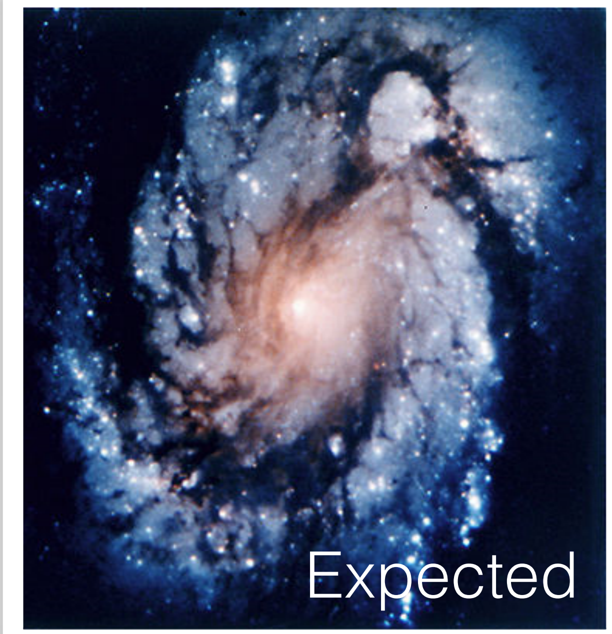
- Telescope diameter: 2.4 m
- Wavelength range: 115 nm to 2.4 μm
- Angular resolution 0.05 arcsec (visible light)
  - 20 x better than ground-based telescope w/o adaptive optics (but now the trend is reversing with the advent of extreme AO)
- Sensitivity ~50x better than ground-based 10 m-class telescopes (still true)
- Instruments: 3 imaging cameras + 2 spectrographs + guiding sensor
- The only serviceable space telescope
  - space rendez-vous with the shuttle
  - was initially supposed to be brought back on ground every 5 years!

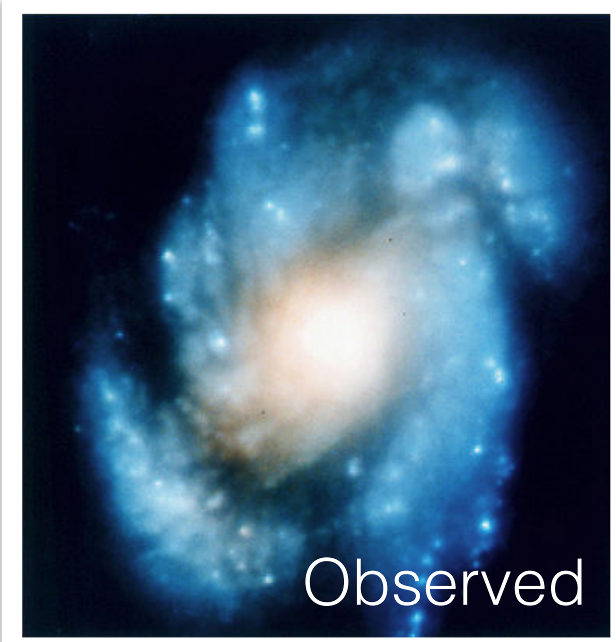
Complexity of the HST



HST's technical challenges

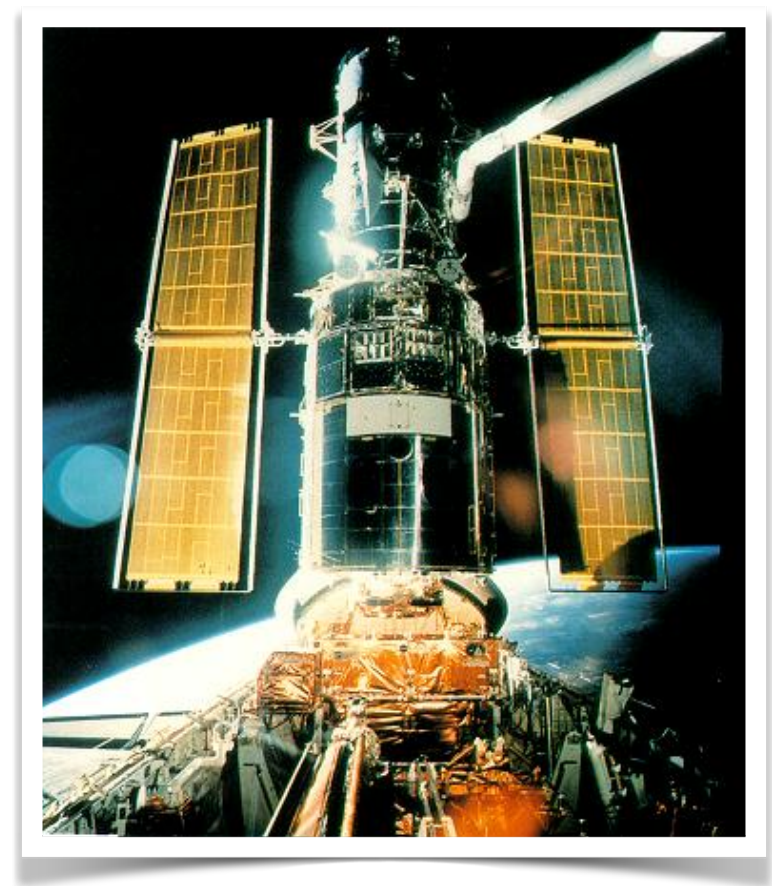
- ✦ Primary mirror: lightweight monolithic reflector
  - thickness: 2 cm (reduce weight)
  - honeycomb structure (resistant to launch)
- ✦ Diffraction-limited —> defects < $\lambda/10$
  - ultraviolet observations: λ = 100 nm
  - new computer-assisted polishing method
- ✦ Final mirror: 2 μm surface error on the sides
  - due to misaligned lens in test equipment for primary mirror (tested separately from full telescope)
  - spherical aberration is a catastrophe: resolution ~ 1 arcsec!

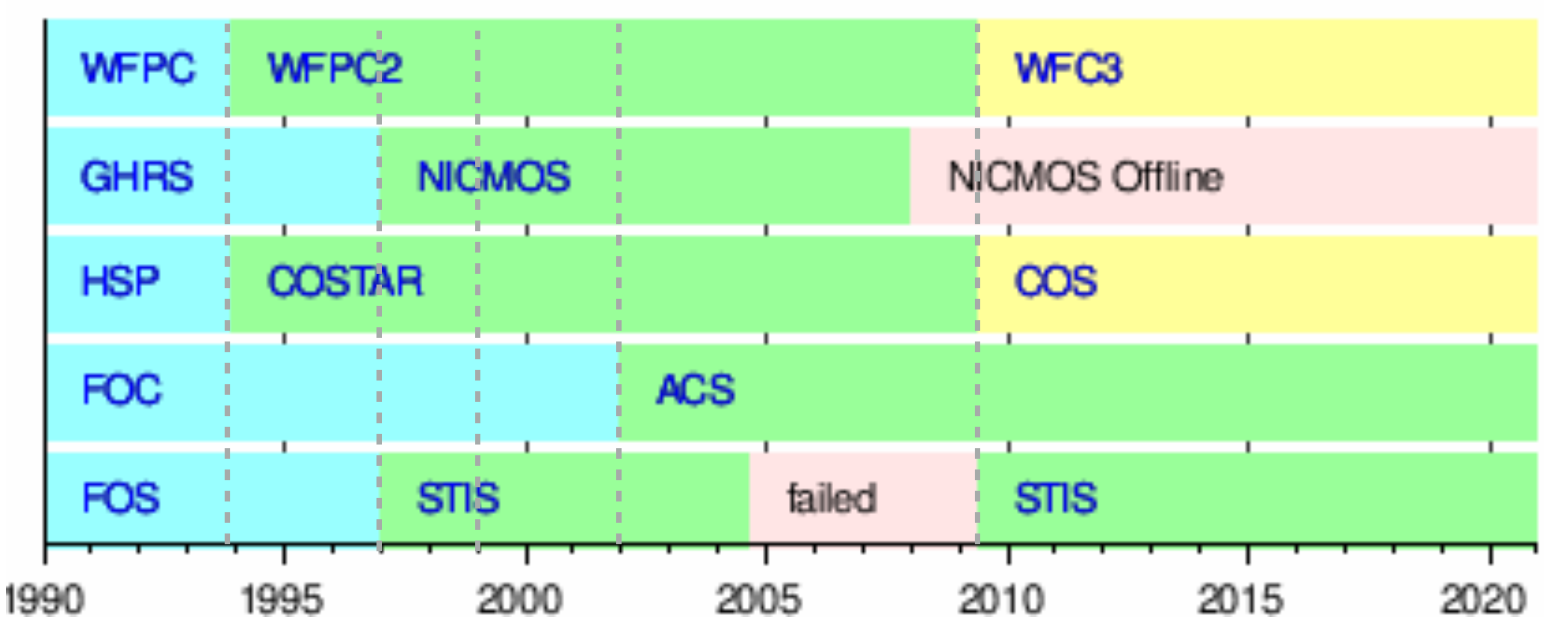




Servicing missions

- ✦ Mirror impossible to replace
  - new instruments —> integrated optical corrector
  - old instruments —> correcting package
- ✦ Missions in 1993, 1997, 1999, 2002, 2009
  - replacement of instruments, gyroscopes, solar panels, batteries, etc.
  - various repairs + orbital correction





Wide field camera

Near-IR camera and spectrograph

UV spectrograph

UV / visible / near-IR camera

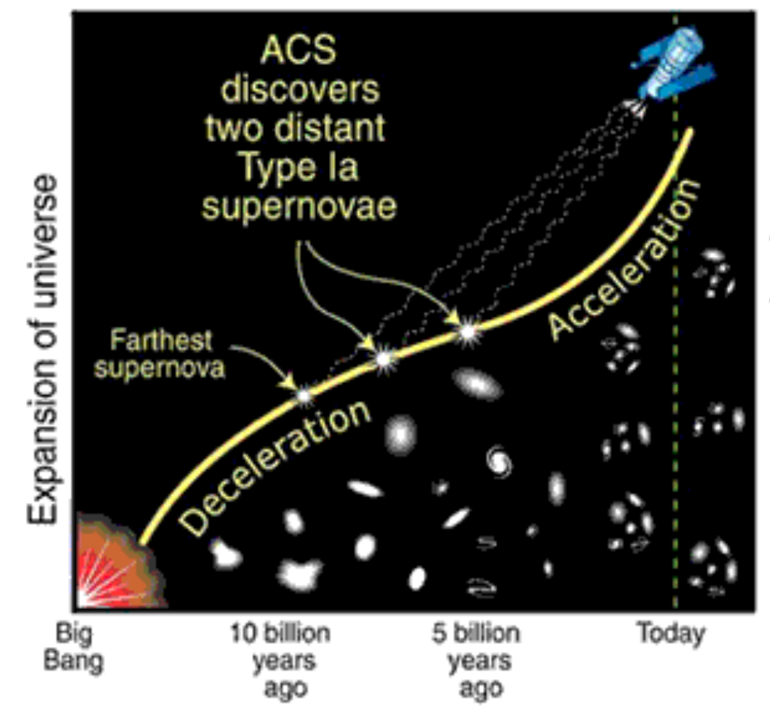
UV / visible / near-IR spectrograph

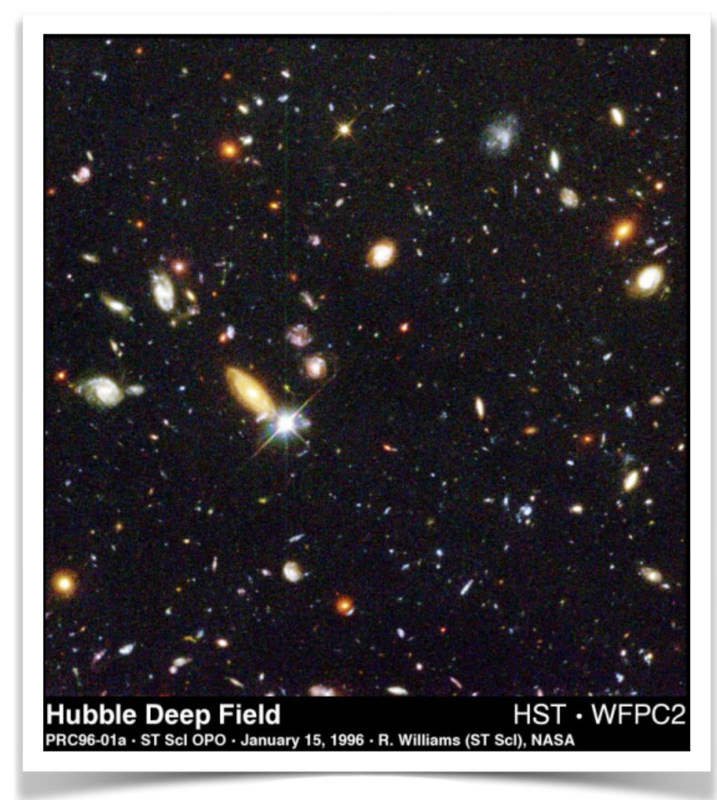
Other challenges

- Thermal / mechanical stability
  - 96 min day / night cycle
  - observations possible even during thermal shock thanks to multilayer insolation, carbon fiber structure, etc
- Future maintenance (without the shuttle)
  - no more servicing missions … unless private partner?
  - de-orbitation: initially foreseen with space shuttle, then external propulsion module considered. Finally capture system installed to enable de-orbit by crewed or robotic mission.
- Budget
  - 400 M$ —> 2.5 G$ (launch) —> ~9 G$ (2010)

Extragalactic discoveries

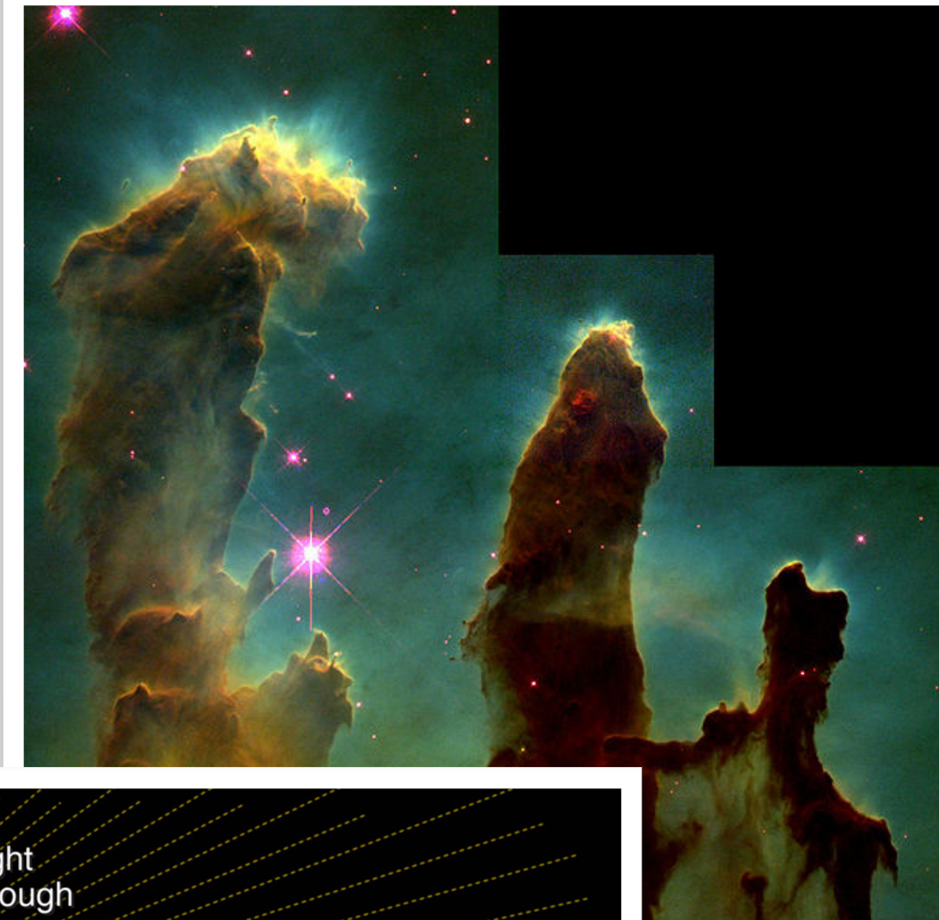
- Estimation of the Hubble constant (H_0)
  - Hubble-Lemaître law: $v = H_0 D$
  - HST —> measures D with Cepheids
- Expansion of the Universe
  - remote supernovae —> accelerating expansion!
  - requires dark energy
- Black holes at the center of galaxies
- Hubble Deep Field (10-day exposure): « primordial » galaxies

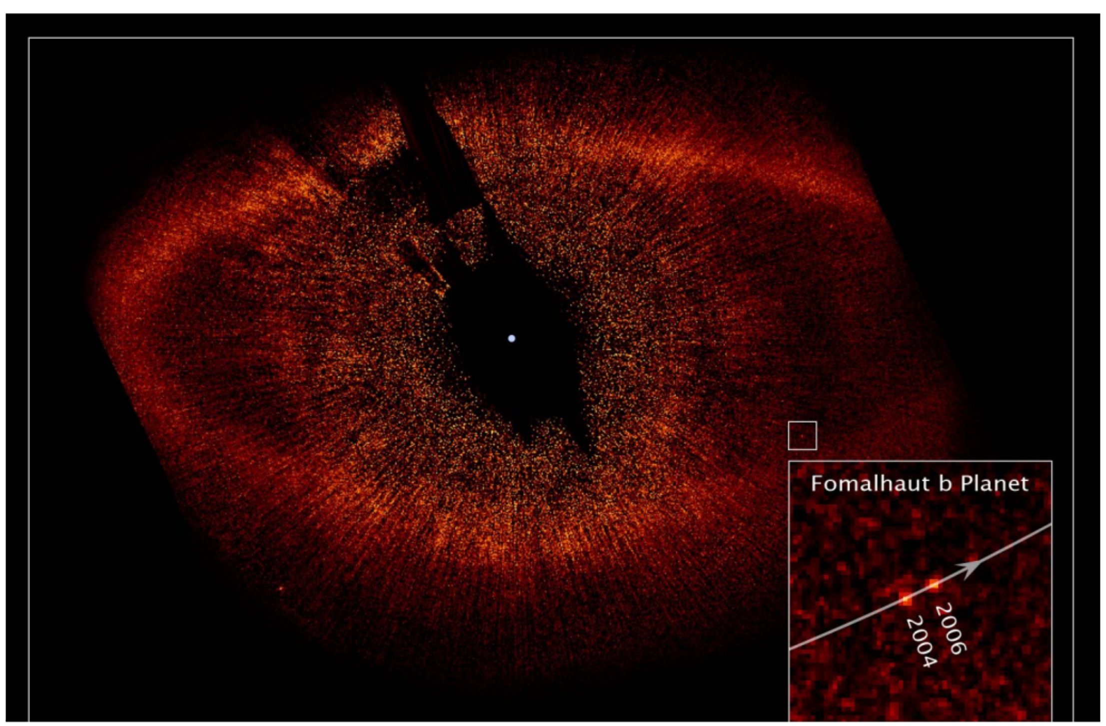


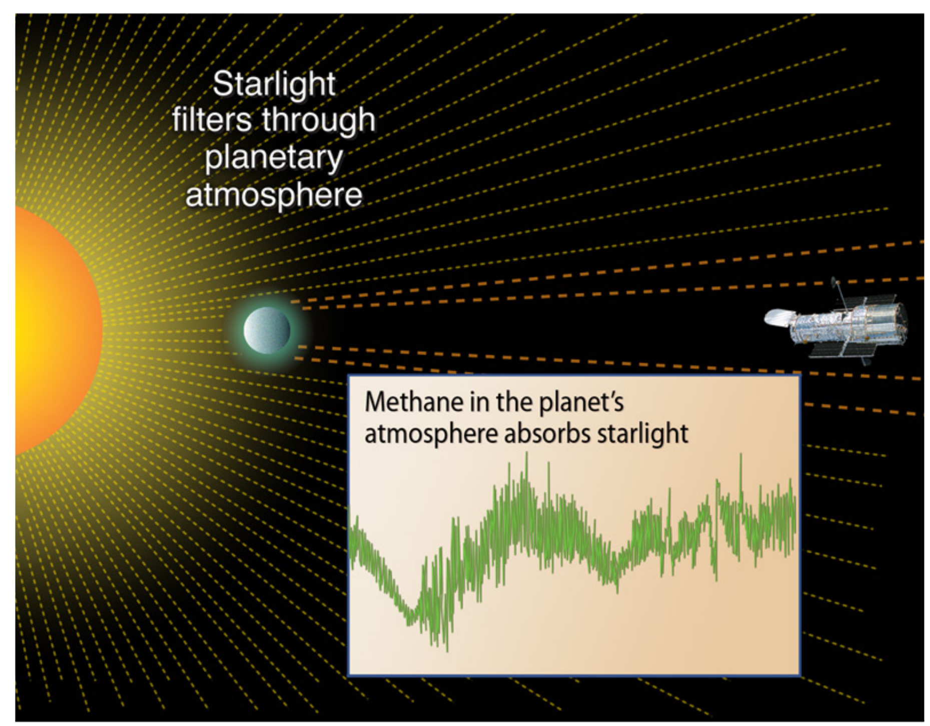


Galactic discoveries

- Star / planet formation
- Extrasolar planets
  - confirmation of planetary nature (transit)
  - first images of planetary systems
  - first exoplanet spectrum —> composition

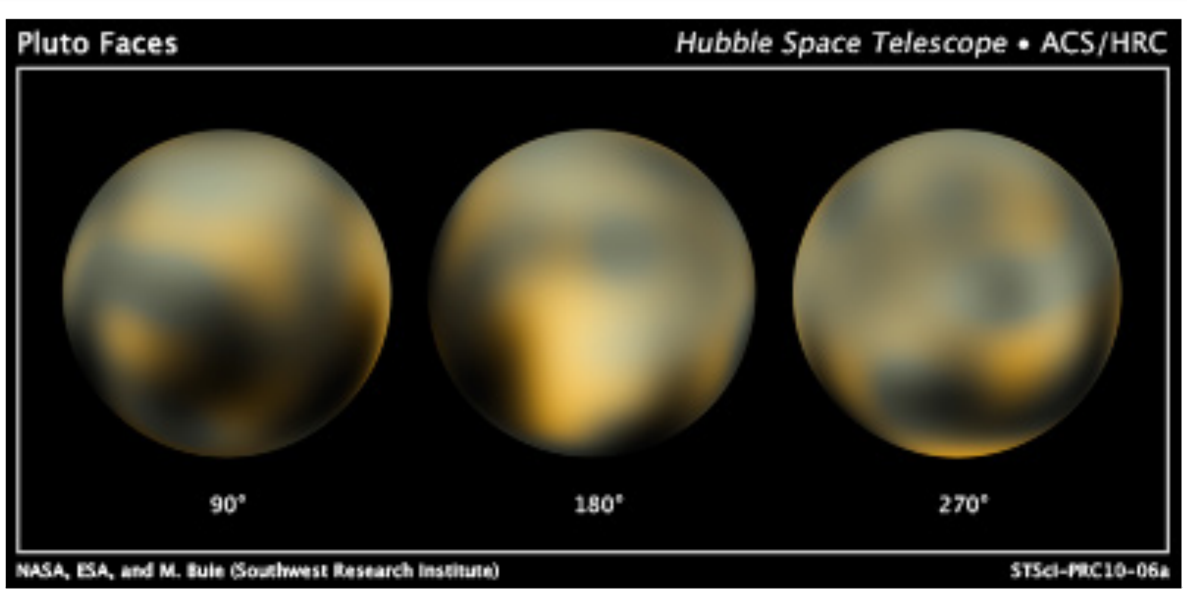


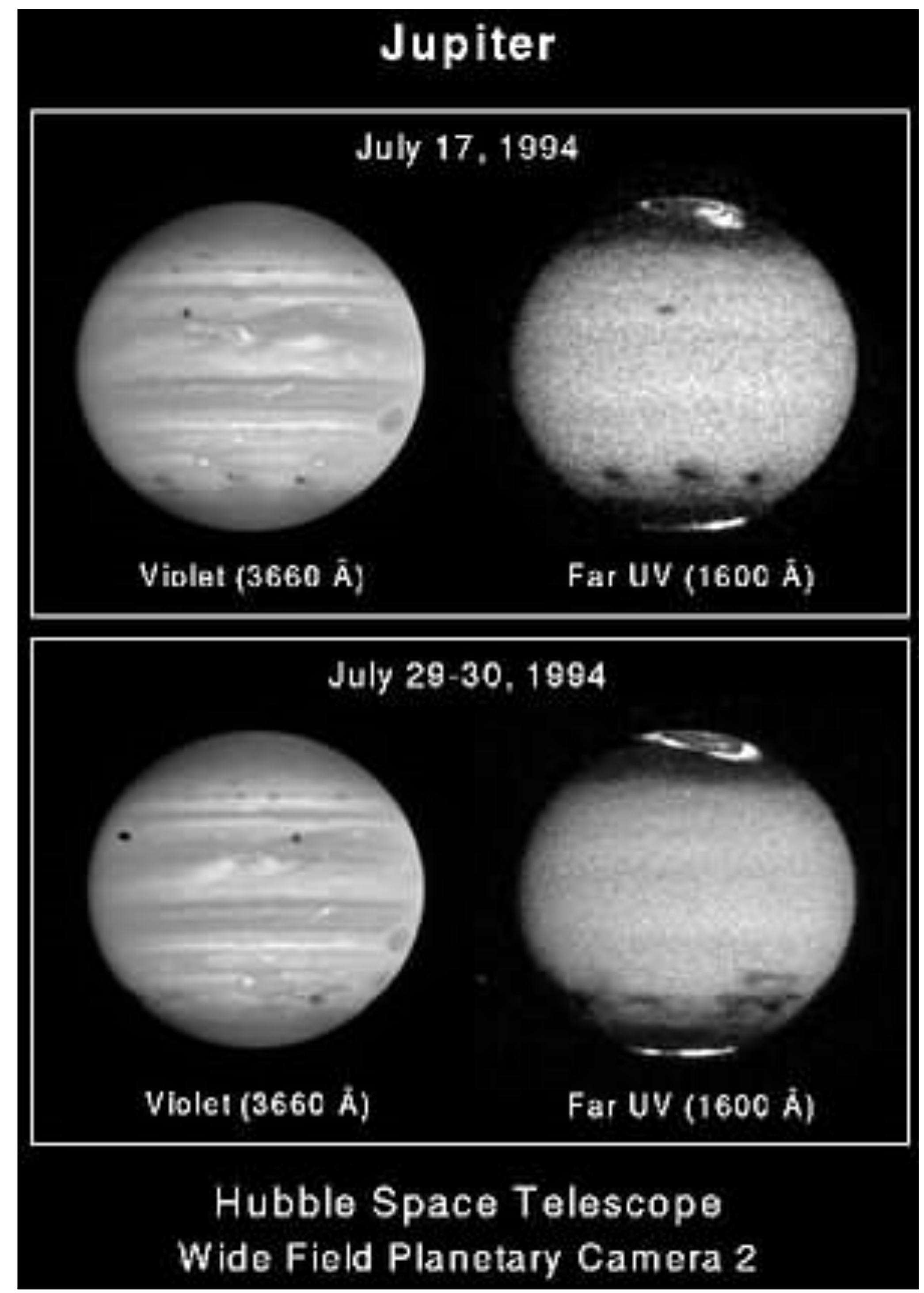




Solar system

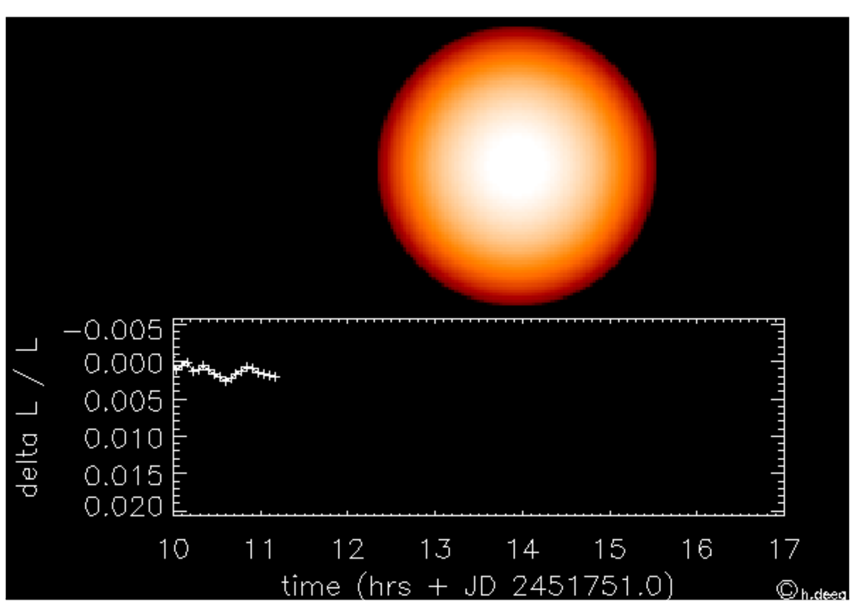
- Giant planets: aurorae, impacts, atmospheric dynamics, etc.
- Dwarf planets: Pluto's surface, small bodies in Solar System, etc.

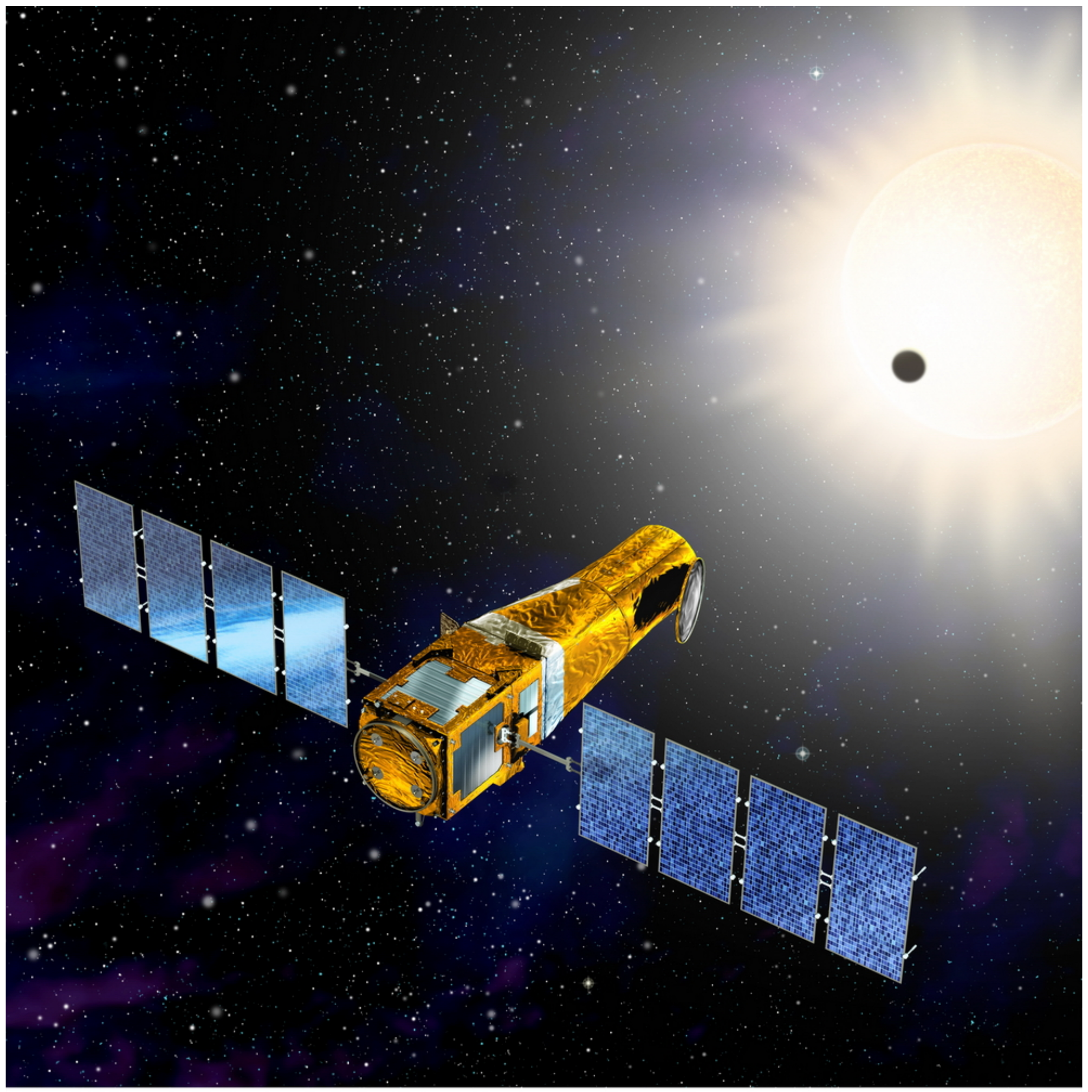




Other examples:
CoRoT / Kepler / TESS

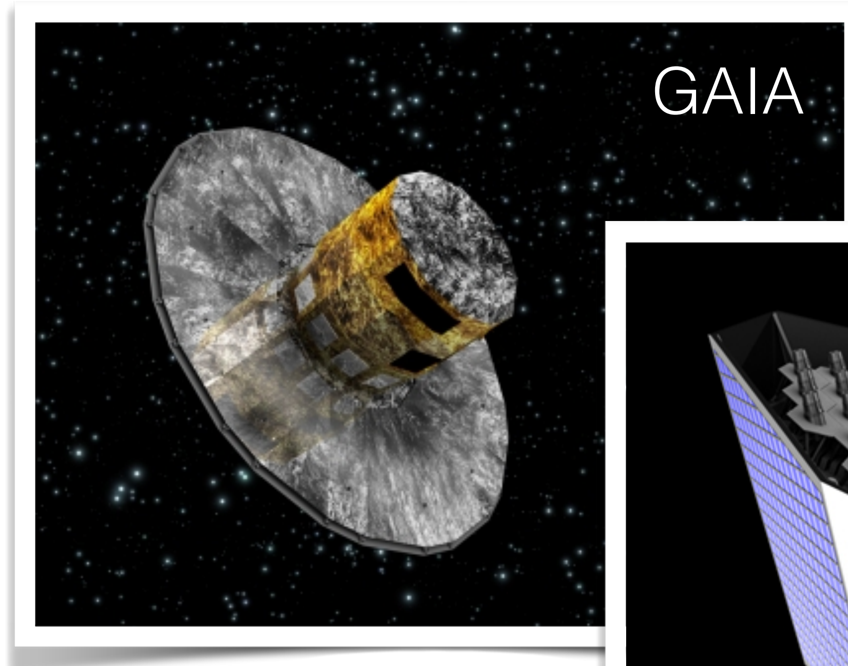
- ✦ Small telescopes providing high-precision photometry
  - down to 10 - 100 ppm
- ✦ Exoplanet detection by transits
  - first rocky planets
  - several potentially habitable planets
- ✦ Asterosismology

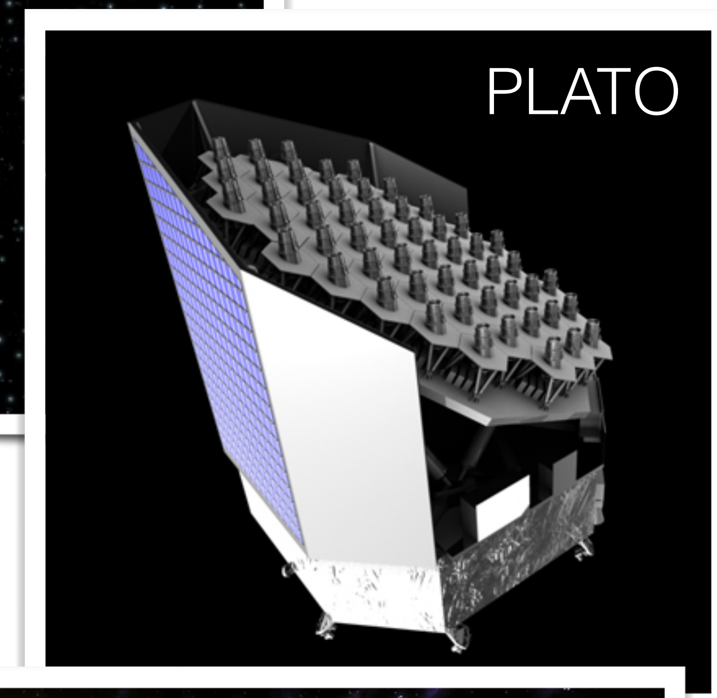


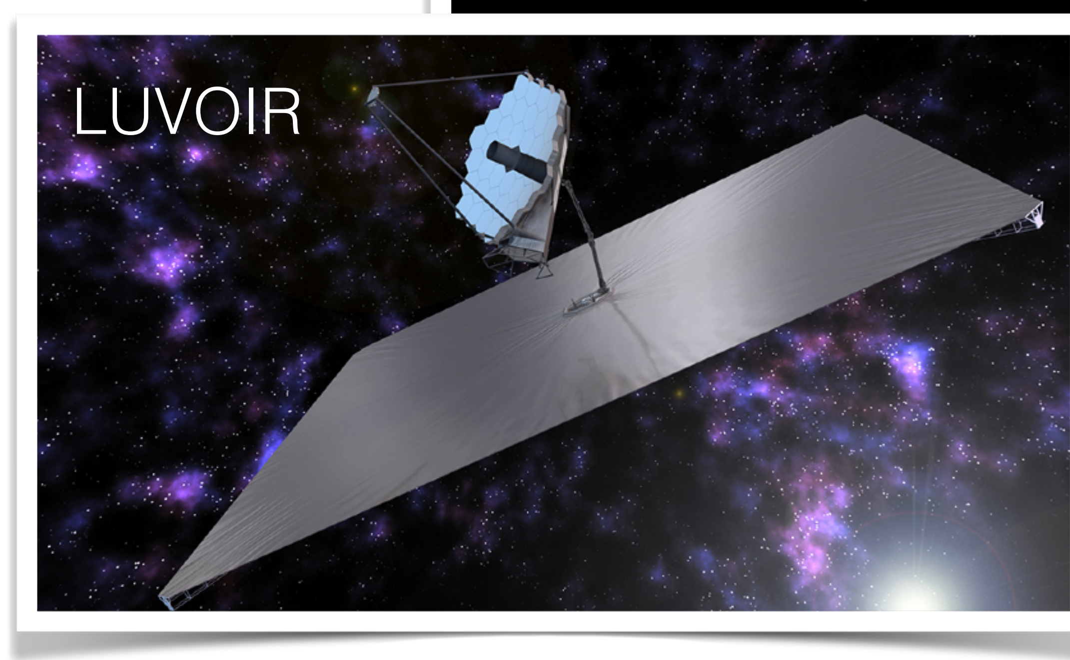


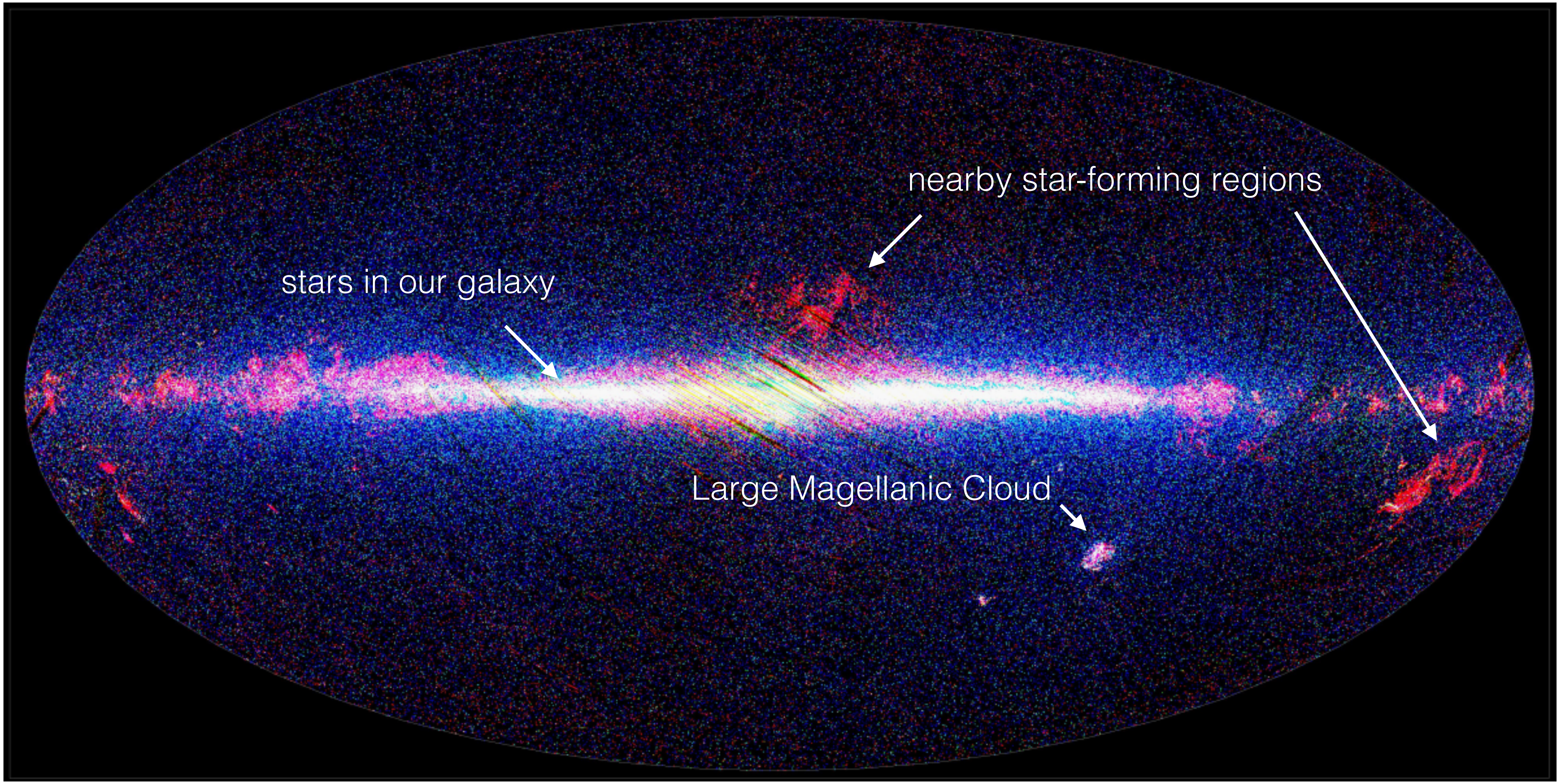
Latest & future missions

- GAIA (ESA, 2013)
  - 3D map of our Galaxy
  - 1,000,000 stars (position, velocity)
  - 106 CCDs —> 1 billion pixels
  - hyper-stable SiC structure
- ESA Cosmic Vision
  - Solar Orbiter (2020, on its way)
  - EUCLID (2023): dark energy / dark matter
  - PLATO (2026) and ARIEL (2029): extrasolar planets
- NASA's future large optical telescopes
  - Roman Space Telescope (2.4 m, 2027)
  - LUVOIR/HabEx concept (~6 m, 2040s)







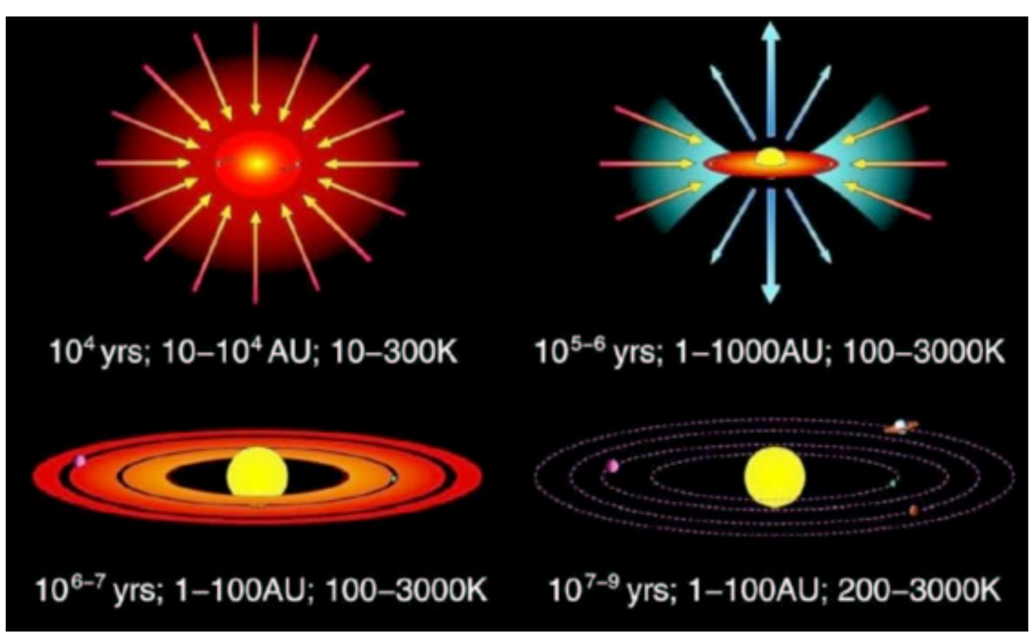


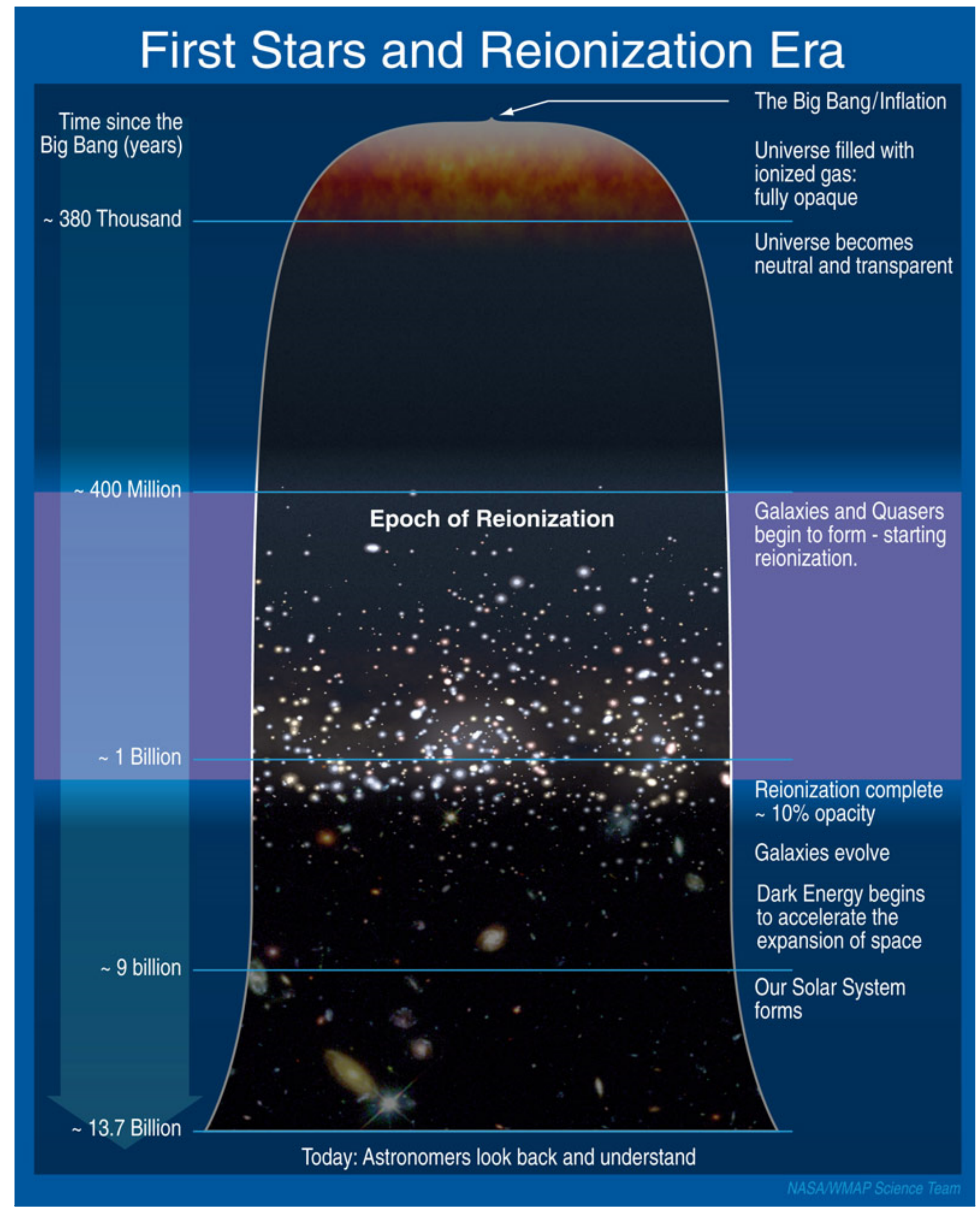
Mid-infrared

From $\lambda = 3$ μm to $\lambda = 30$ μm

Astrophysical interests

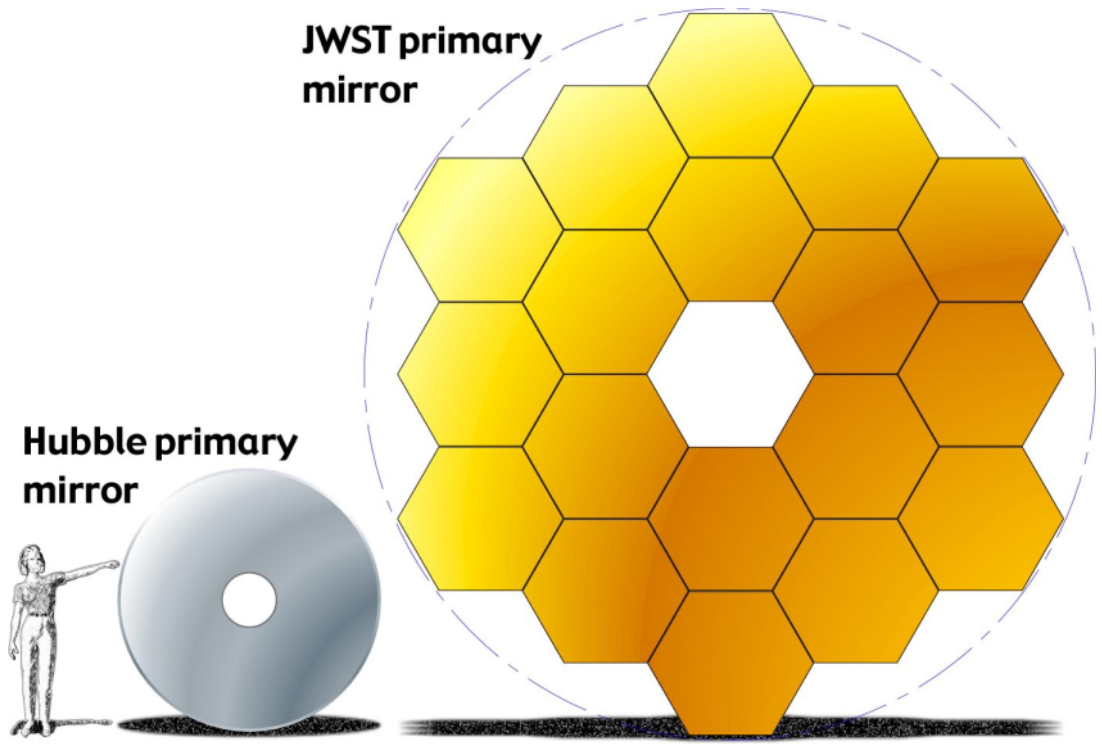
- Primordial universe
  - high redshift: visible shifted to mid-IR
  - first stars & galactic assembly
- Thermal emission @ 100 - 1,000 K
  - star / planet formation & exoplanets
  - mid-IR can see through dust!





James Webb Space Telescope

- ✦ Biggest space telescope
  - telescope diameter: 6.5 m
  - wavelength range: 0.6 - 29 μm
  - diffraction-limited beyond 2 μm
- ✦ NASA project with ESA and CSA contribution
- ✦ Launched from Kourou with Ariane 5 on Dec 25, 2021



A long testing campaign

Testing / shipping highlights

Aug 2019 @ Northrop Grumman
(JWST fully assembled)

Oct 2020 @ Northrop Grumman (final acoustic tests completed)

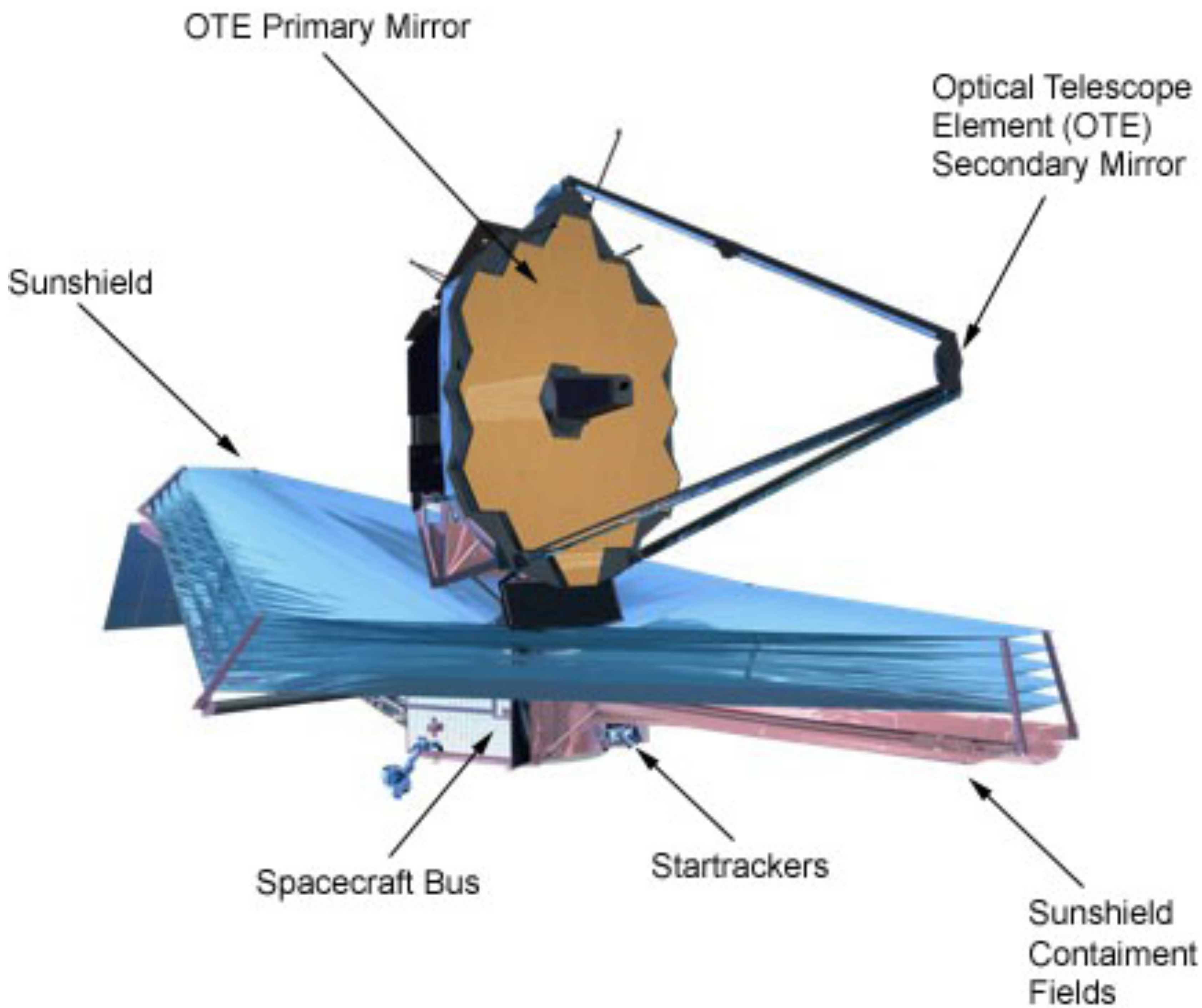
Oct 2021: arrival at Kourou!

The JWST budget

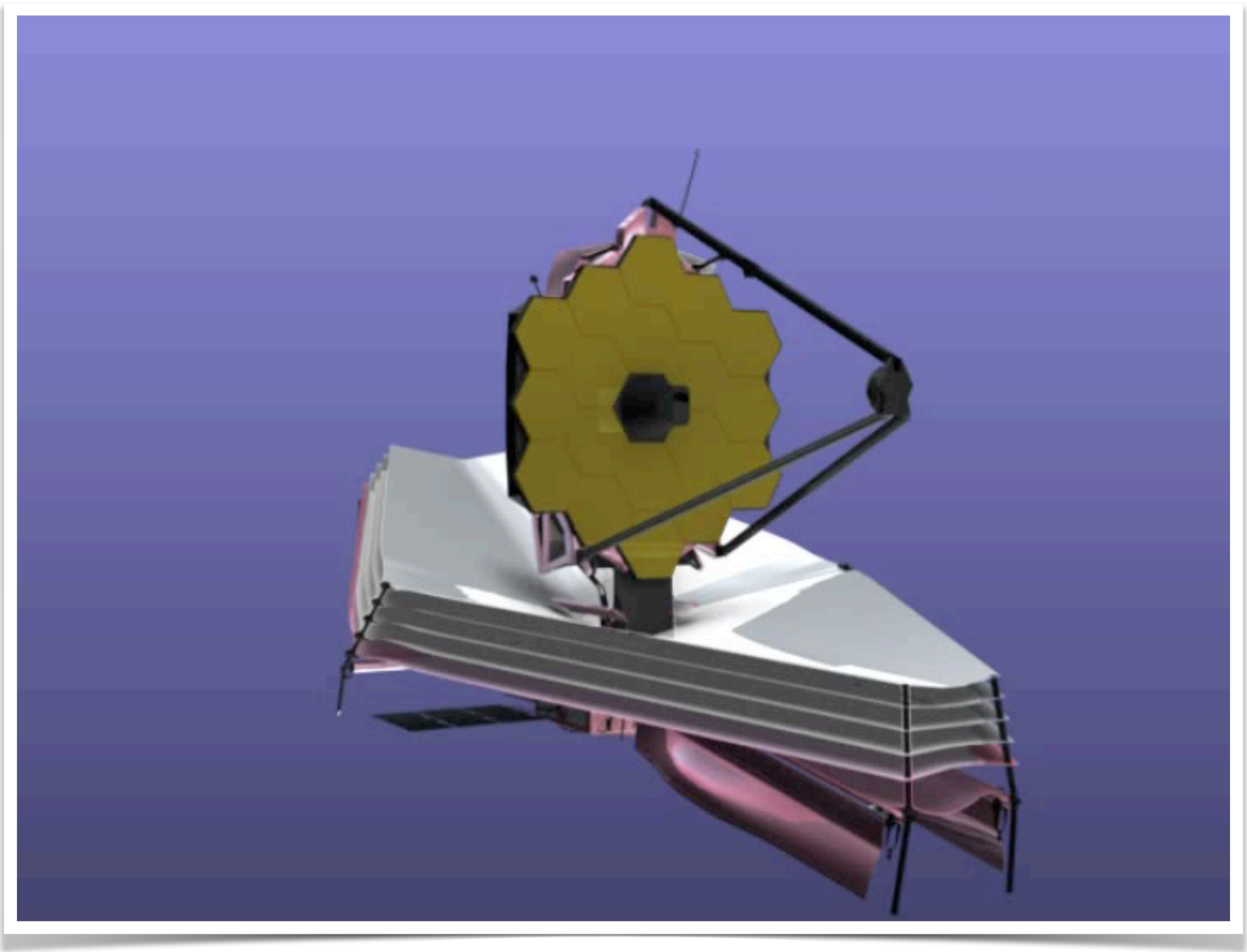
	Year	Launch date	Budget	
	1997	2007	0.5 B$	
	1998	2007	1 B$	
	1999	2007/2008	1 B$	
	2000	2009	1.8 B$	
	2002	2010	2.5 B$	
	2003	2011	2.5 B$	
	2005	2013	3 B$	
	2006	2014	4.5 B$	
	2008	2014	5.1 B$	
	2010	2015/2016	6.5 B$	
almost cancelled!	2011	2018	8.7 B$	congress-approved cost cap
	2018	2020	9.7 B$	updated cost cap
	2020	2021	≥ 10 B$ (incl. operations)	

JWST size = tennis court!

JWST design

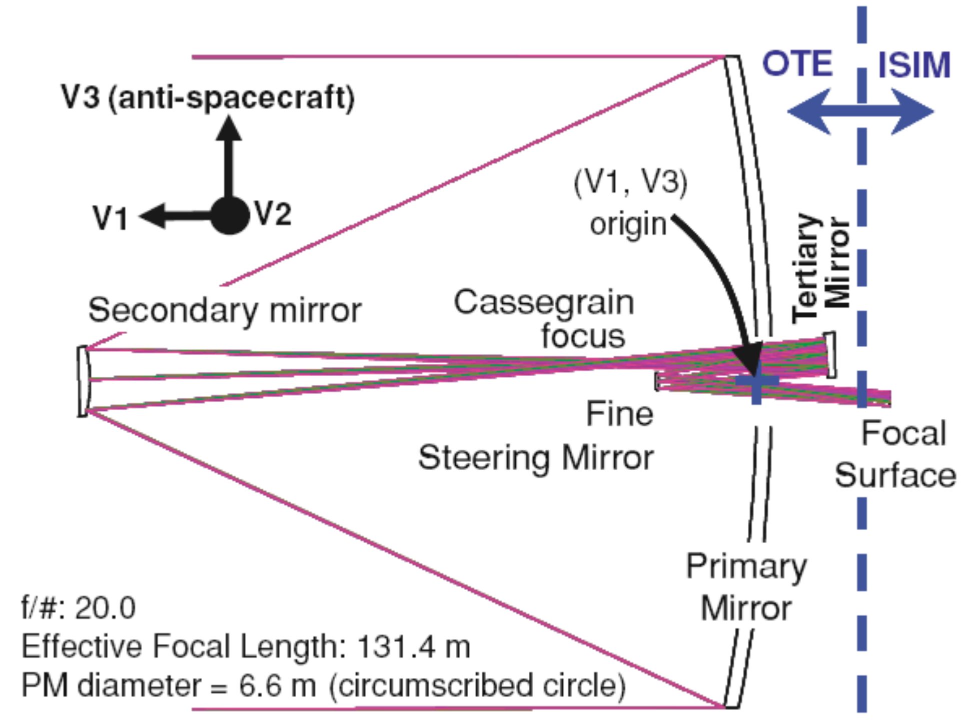

OTE Primary Mirror
Optical Telescope
Element (OTE)
Secondary Mirror
Sunshield
Spacecraft Bus
Startrackers
Sunshield
Contaiment
Fields

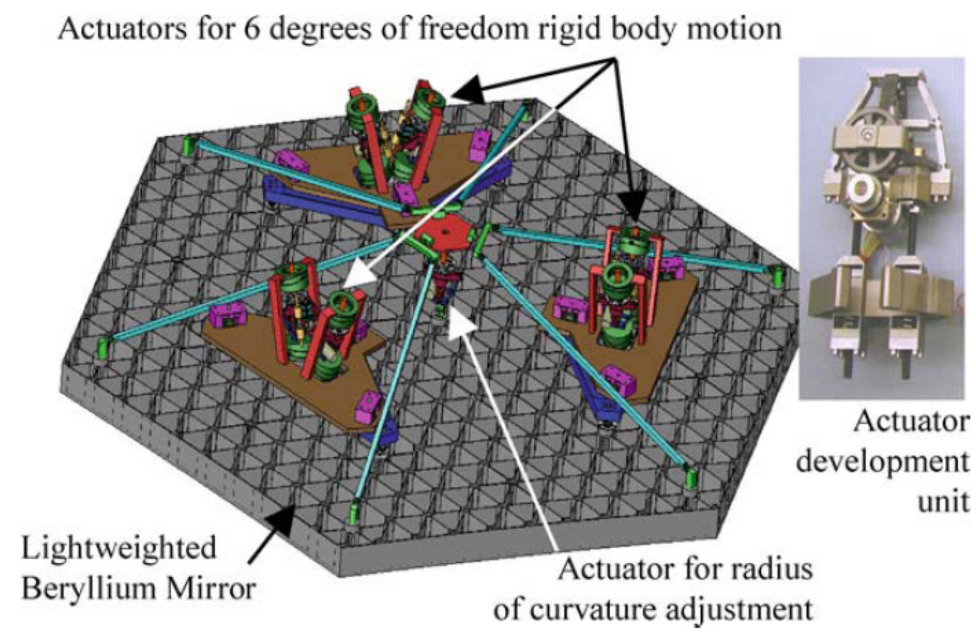
Deployable telescope



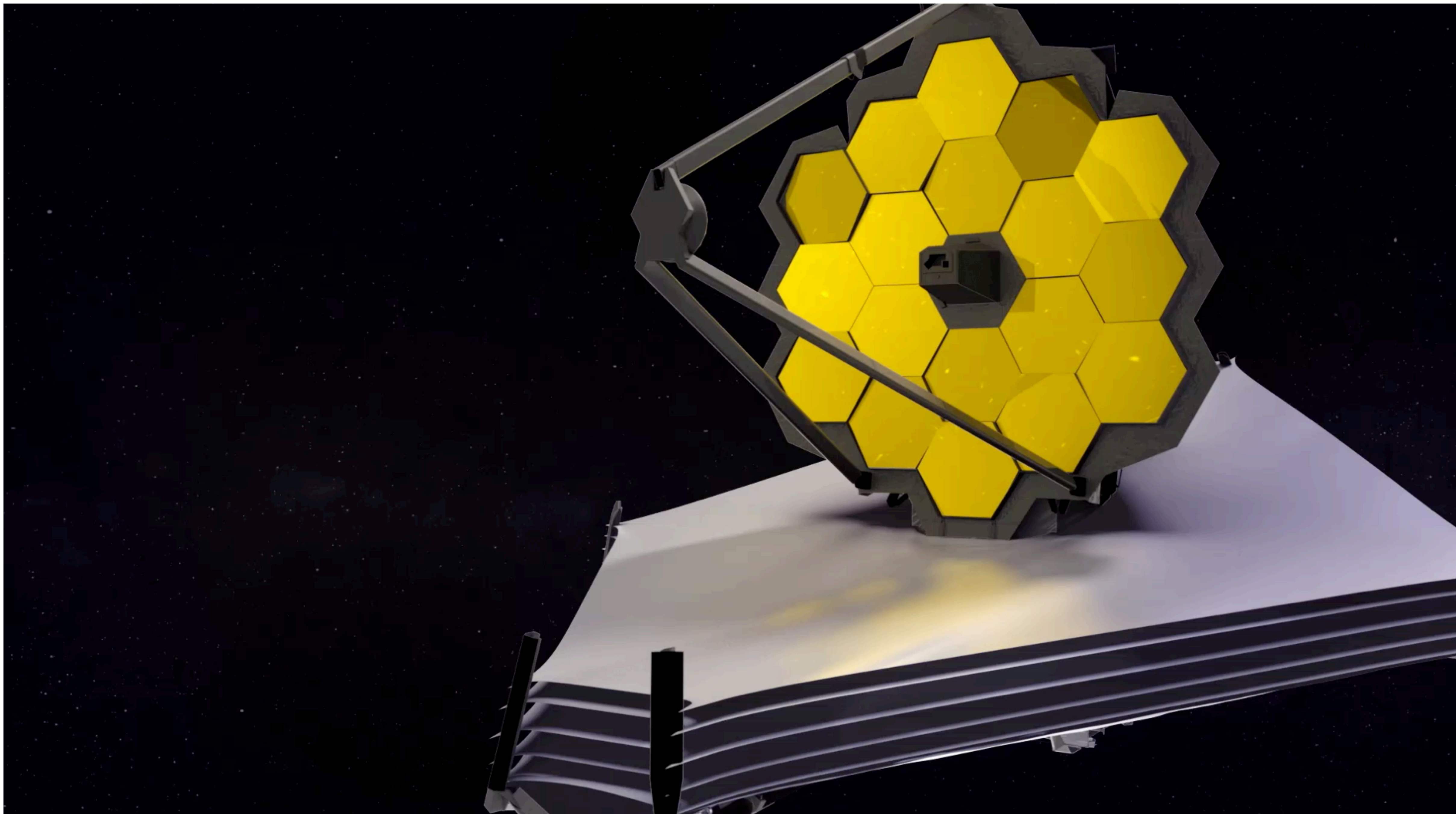
Lightweight segmented mirror

- ✦ Beryllium mirror, 10x lighter than HST by unit surface
  - high strength / weight ratio
  - high stiffness, low deformation
  - honeycomb design
  - gold coating
- ✦ Segment alignment control
  - several levels of sensing and correction
  - final alignment accuracy < 100 nm
  - re-aligned every 2 weeks



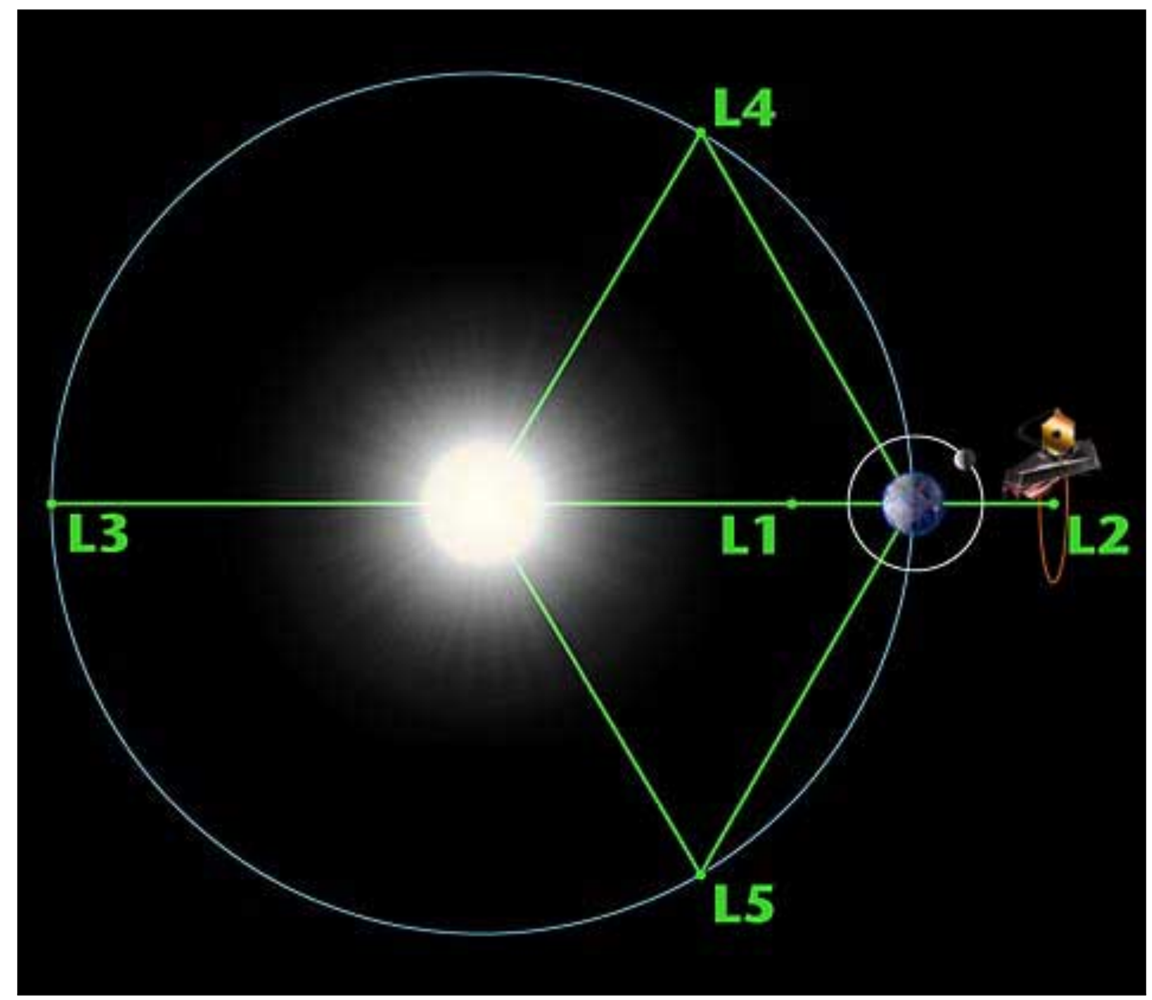


Telescope initial phasing



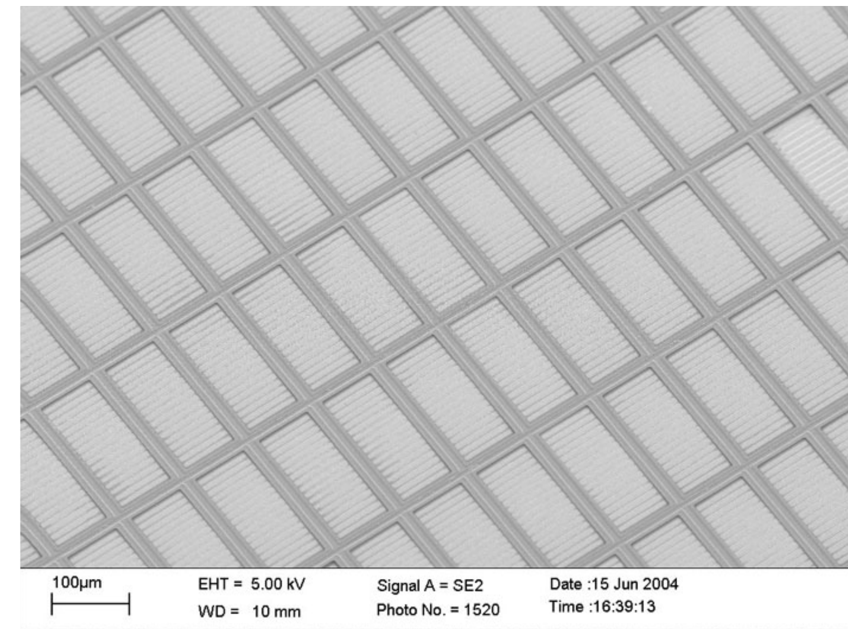
Cooling

- Lagrange L2 point
- Mirror: passive cooling to 50 K
- Innovative sun shield
  - 5 coated polymer-film layers
  - reflects light without heating
  - thickness ~ 30 µm
  - resistant to micro-meteorites
- Instruments: cryogeny

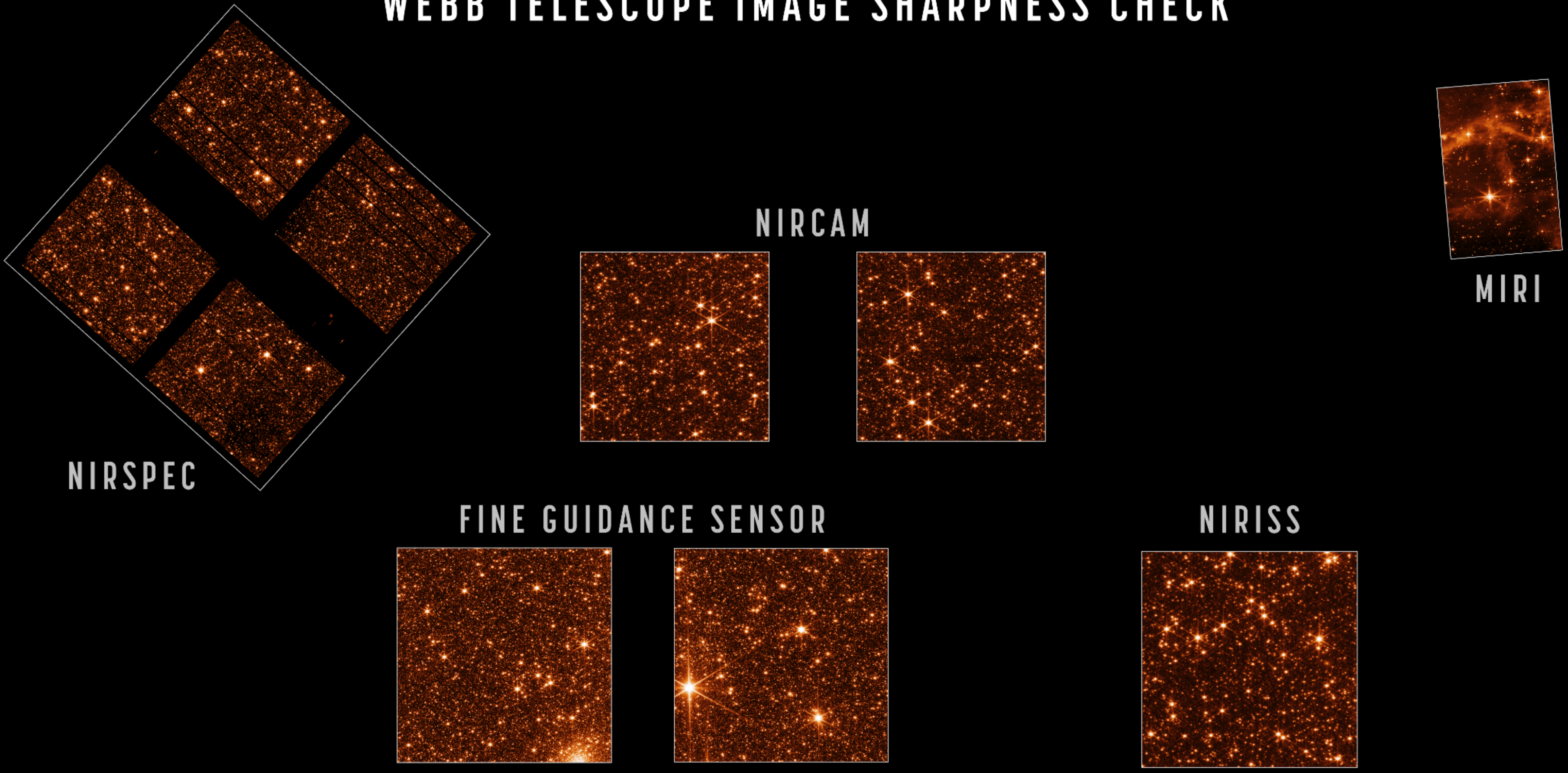


Instruments

- ✦ NIRCam: imaging, 0.6 to 5 μm
- ✦ NIRSpec: spectroscopy, 0.6 to 5 μm
    - multi-object —> micro-shutter array (MEMS)
- ✦ NIRISS: wide-field imaging and spectroscopy, 0.6 - 5 μm
- ✦ MIRI: imaging and spectroscopy, 5 - 29 μm
    - non-local active cryogeny @ 6 K (Joule-Thomson cycle with helium)
    - new Si:As detectors

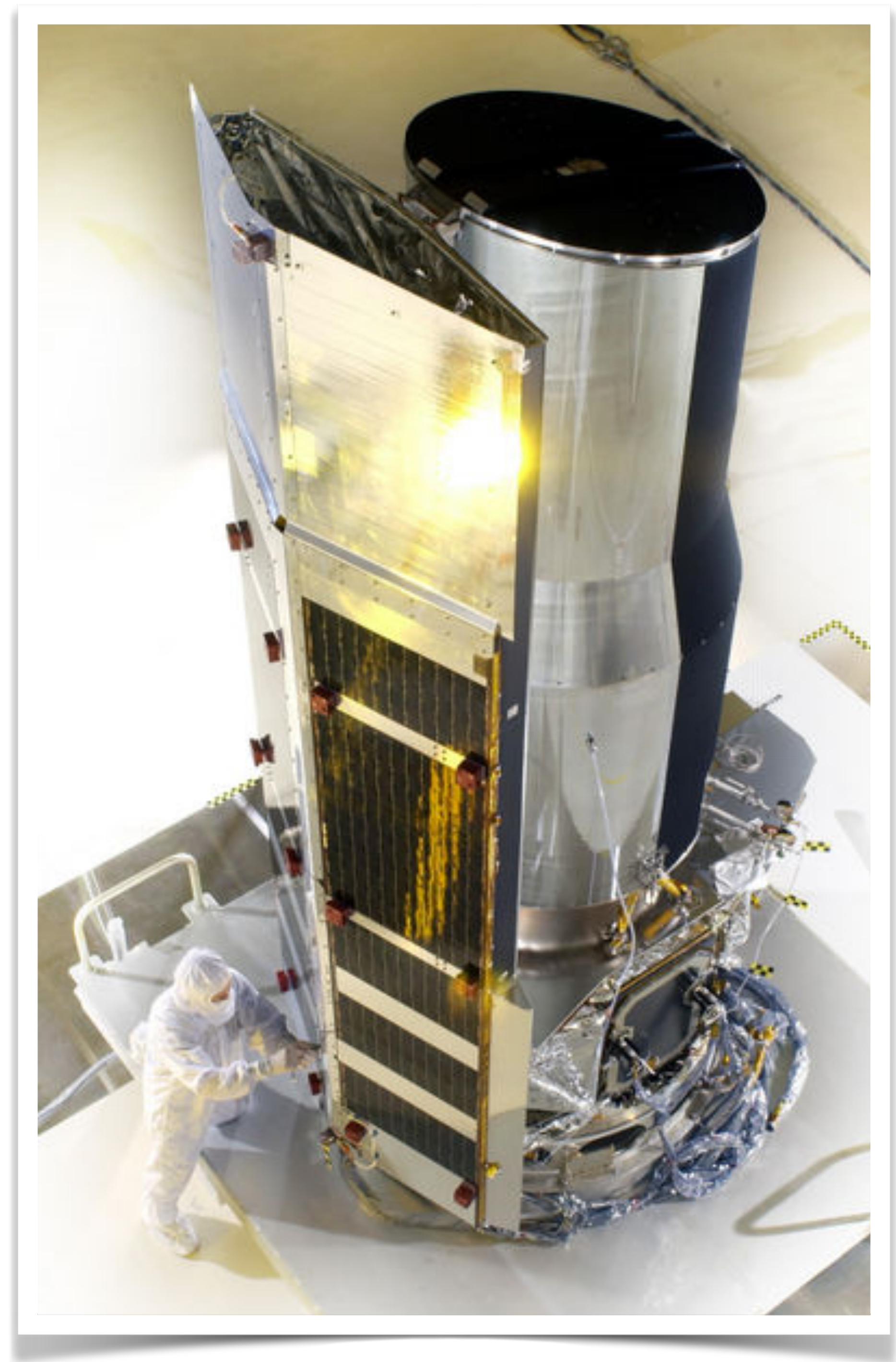


WEBB TELESCOPE IMAGE SHARPNESS CHECK



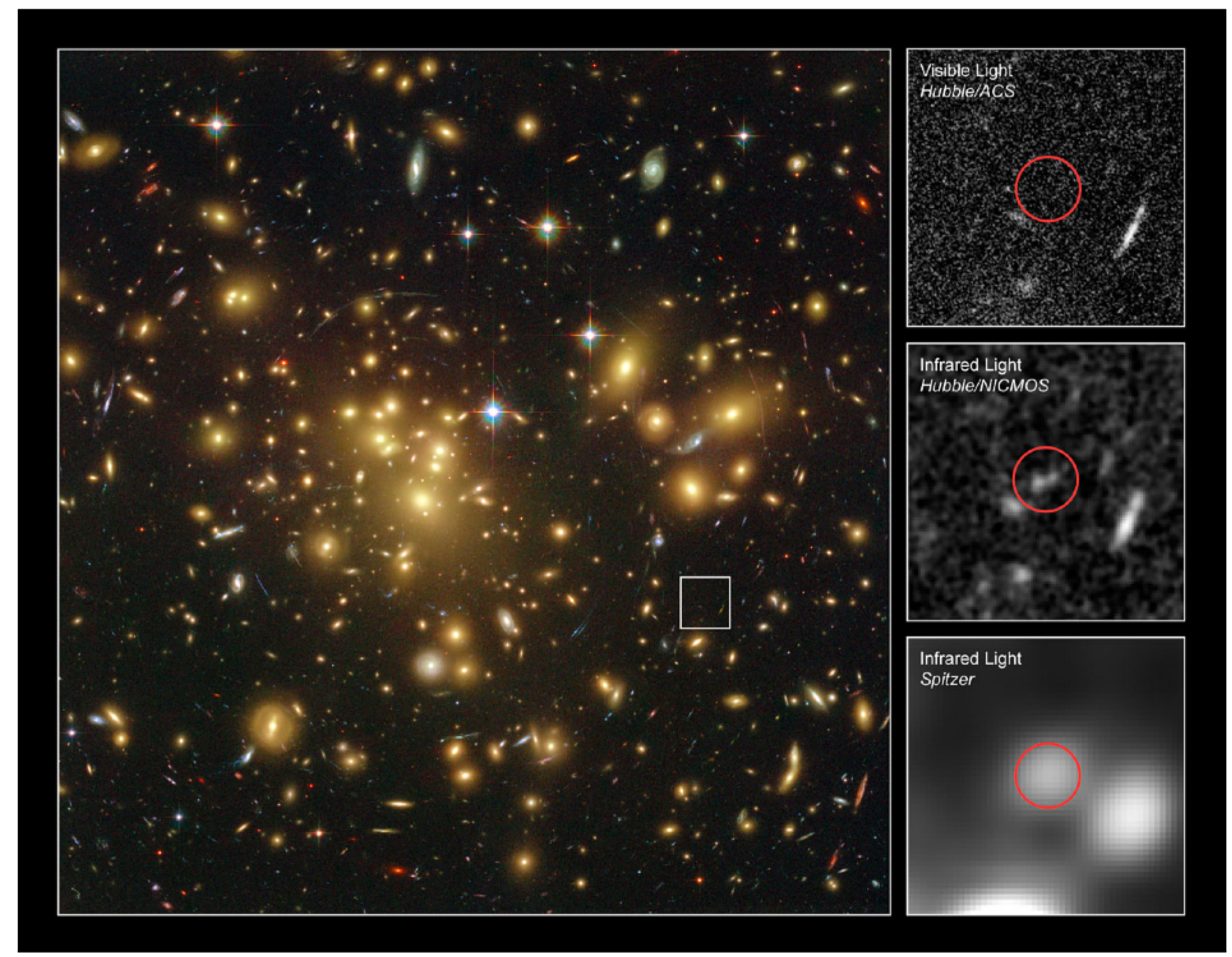
Other missions

- Spitzer Space Telescope (NASA, 2003)
  - 85 cm diameter
  - wavelengths from 3.6 to 160 μm
  - Earth-trailing orbit
  - cooling with 400 liter liquid helium tank (exhausted since 2009, but 'warm' operations only stopped in 2020)
- All-sky surveys
  - AKARI (JAXA, 2006)
  - WISE (NASA, 2009) — cooled to 17 K by solid hydrogen cryostat

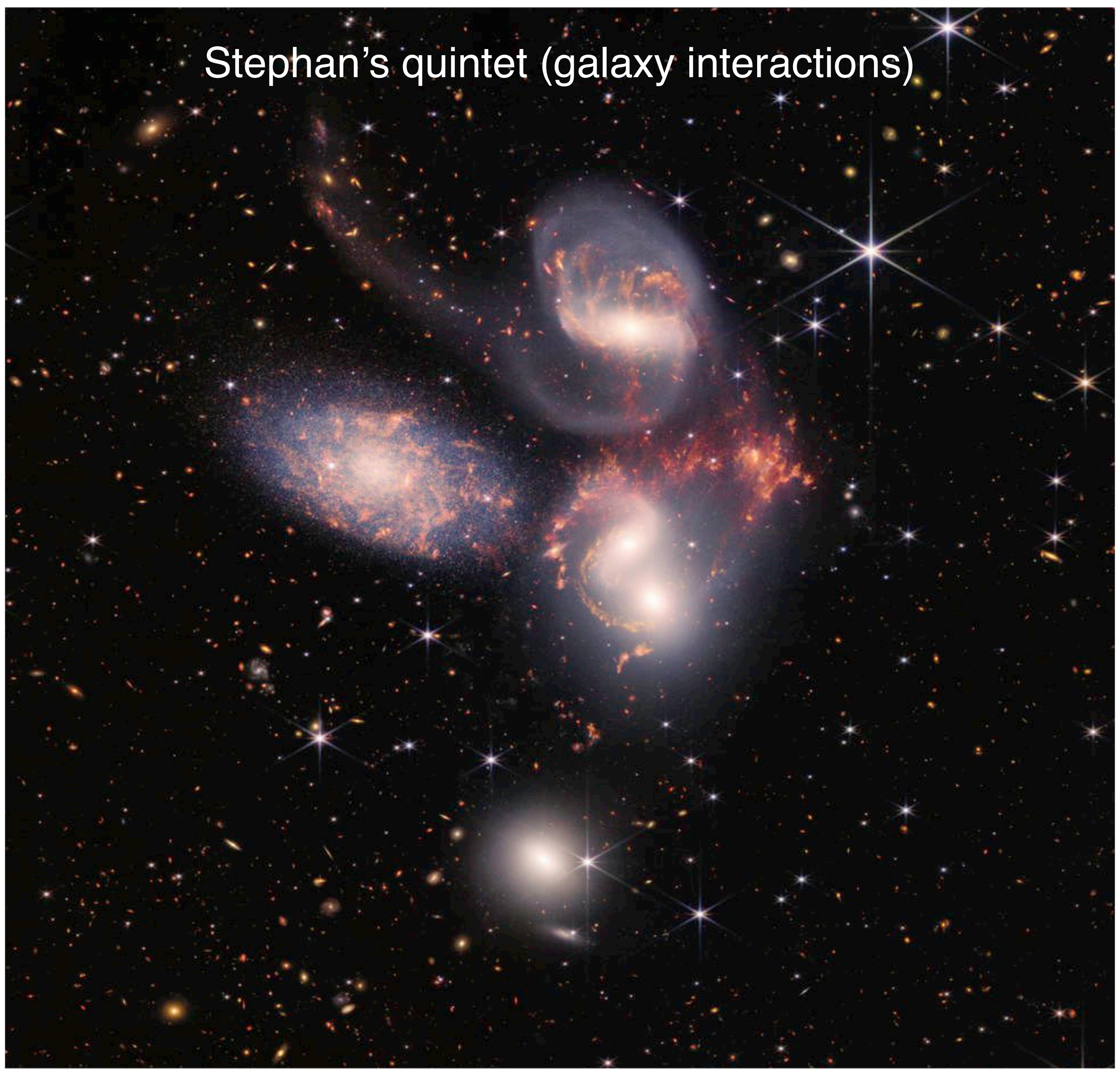


Galaxies

- ✦ First galaxies
- ✦ Galactic structure
  - star forming regions
  - cold dust and gas

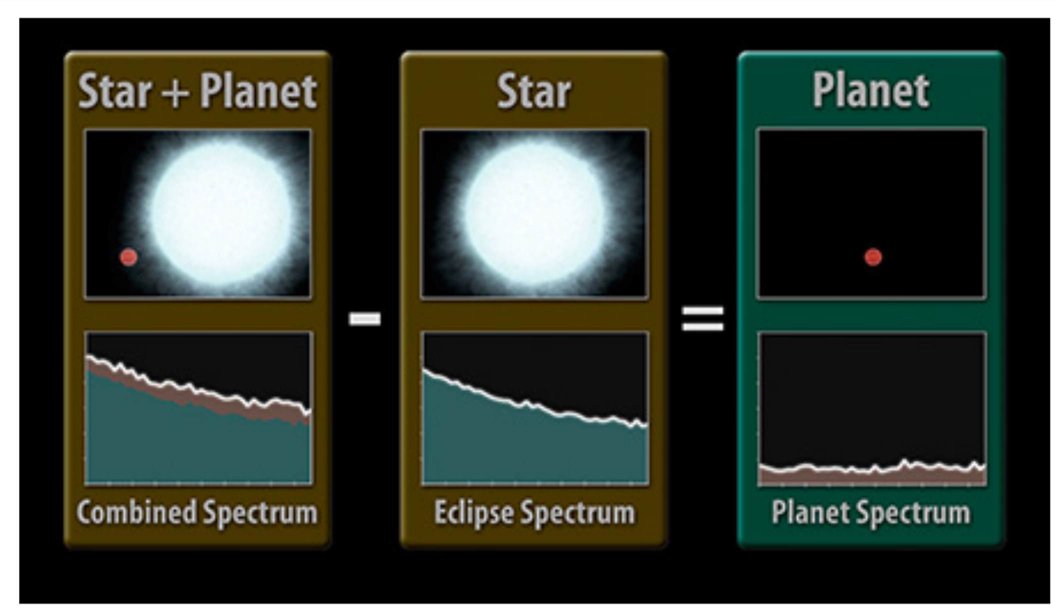


Early JWST highlights

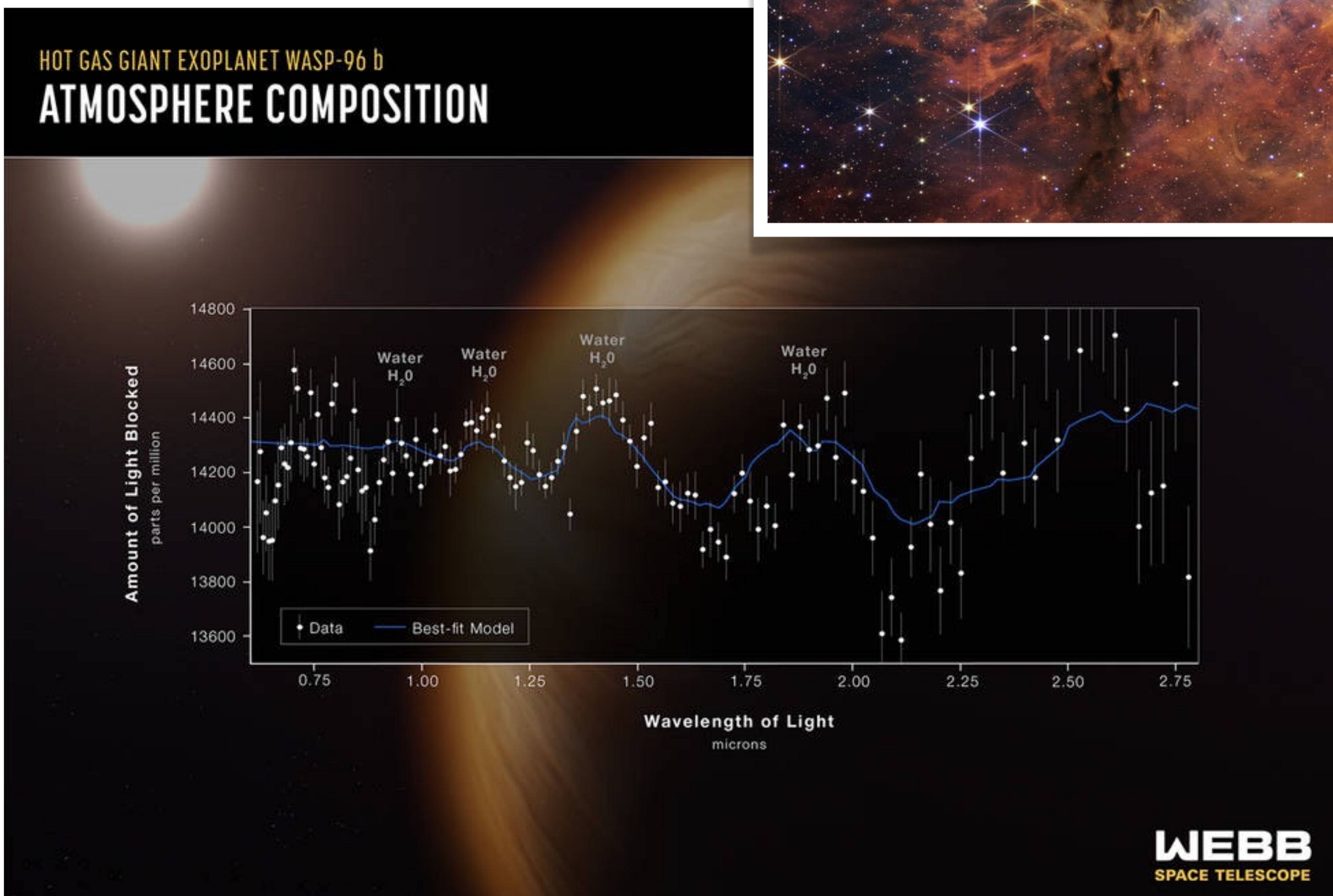


Stars and planets

- Observation of the youngest, forming stars
- Cold brown dwarfs
- Circumstellar disks (IRAS, 1984)
- First measurement of exoplanet temperature (Spitzer, 2006)

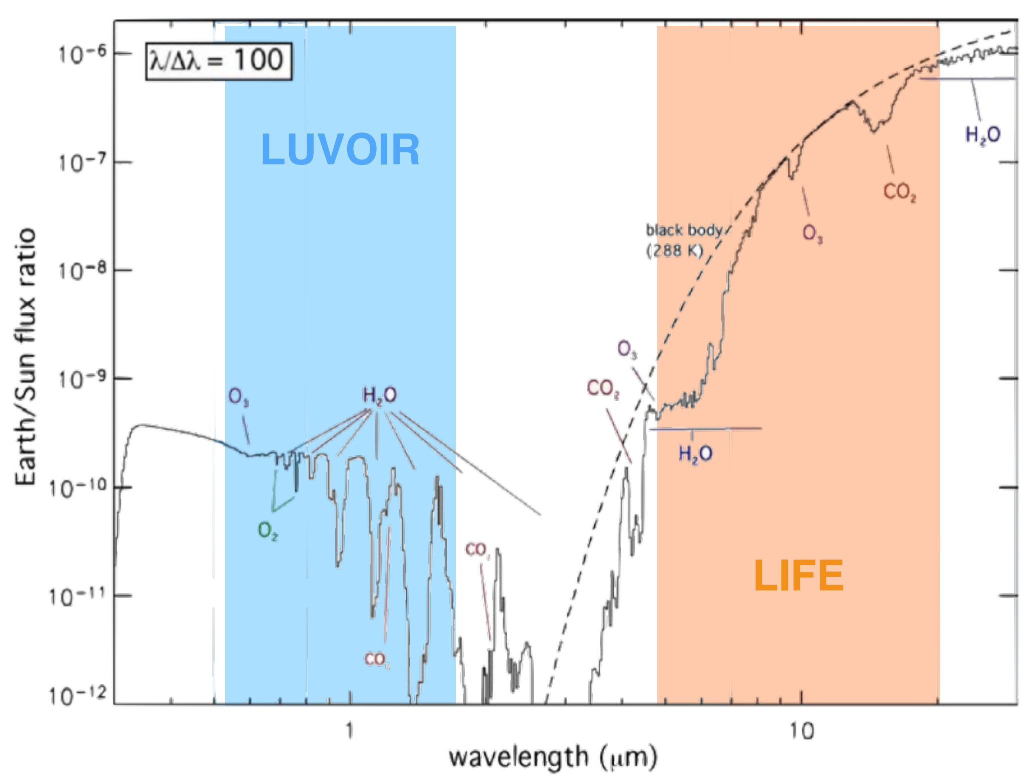


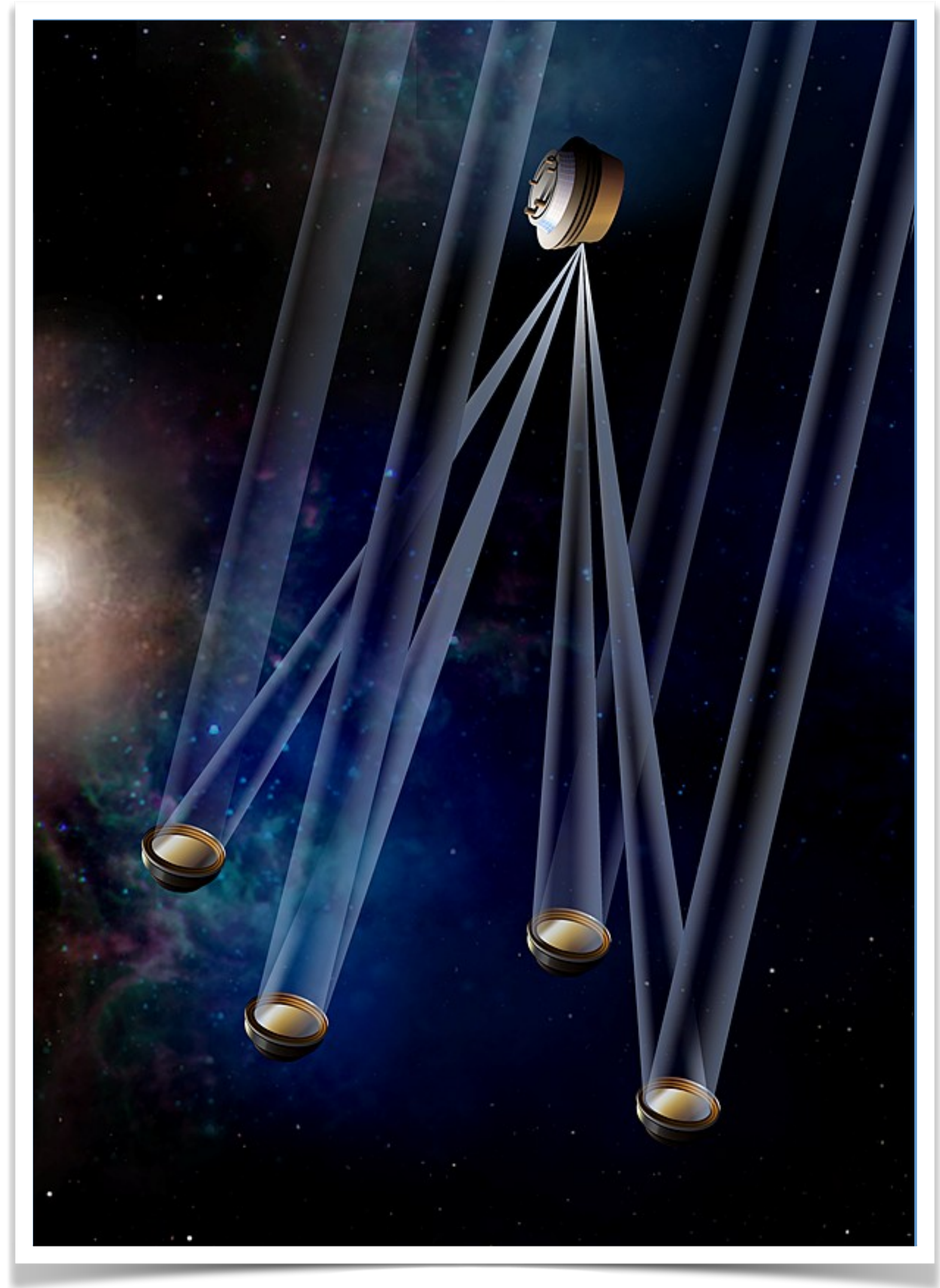
Early JWST highlights

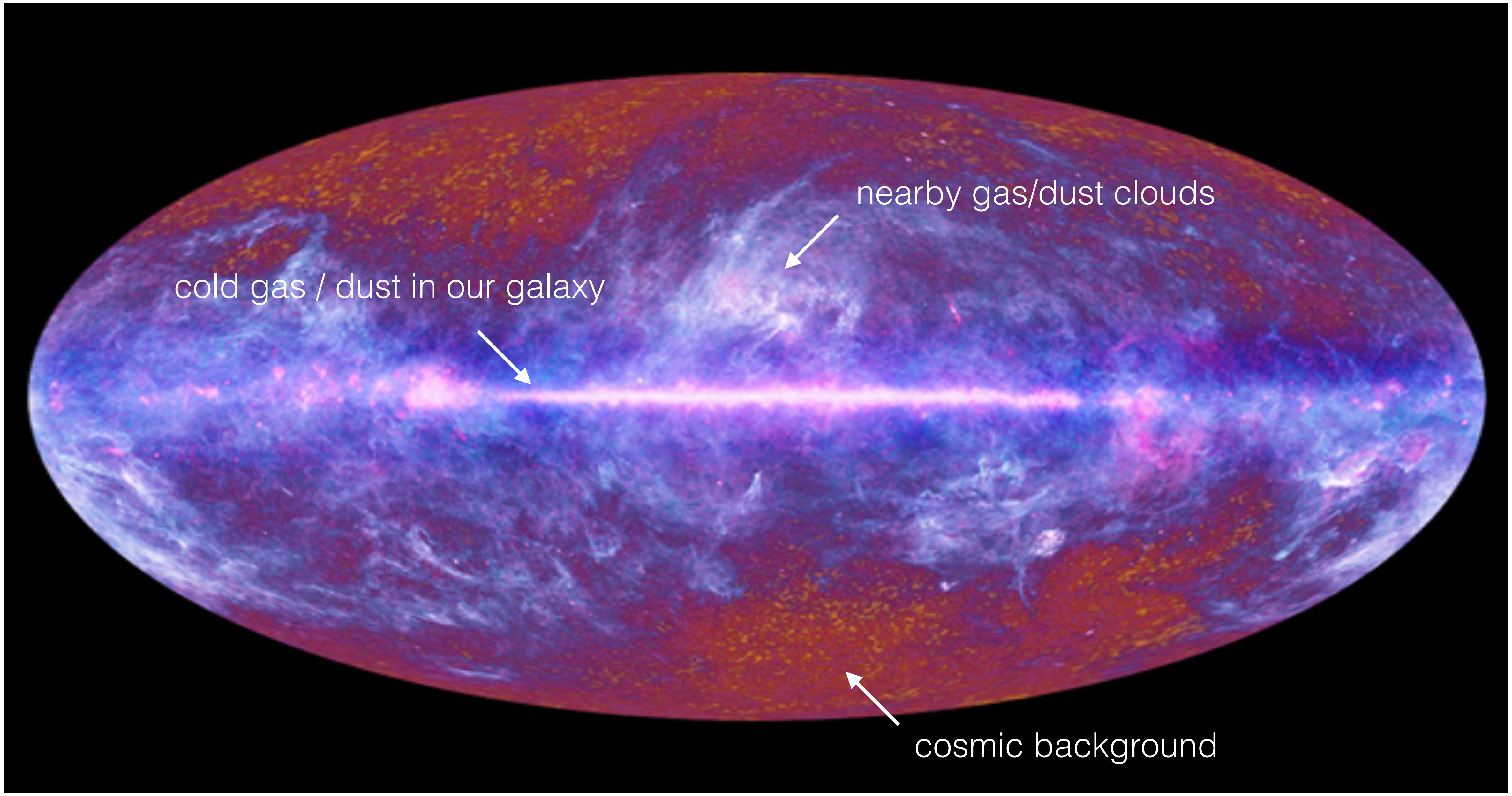


Future: interferometry

- ✦ Formation flying
  - no size limit
  - angular resolution: λ / Baseline
- ✦ Direct imaging of Earth-like planets
  - possible discovery of life!



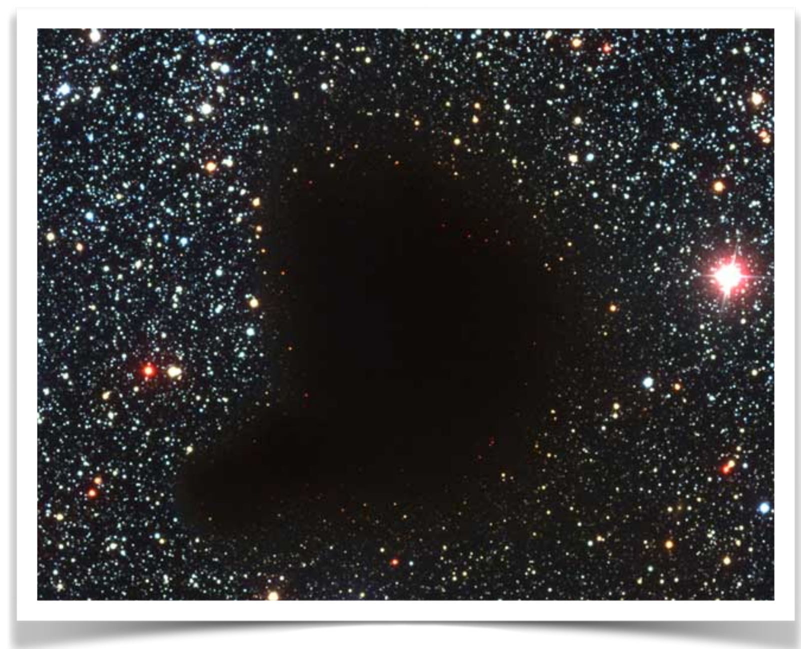


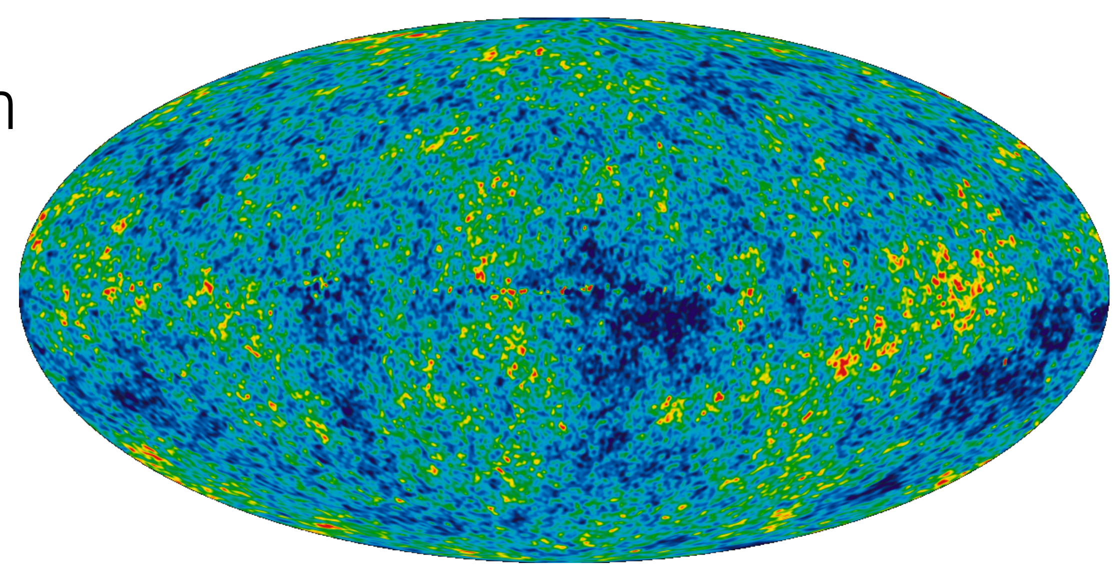


Far-IR / submm / mm

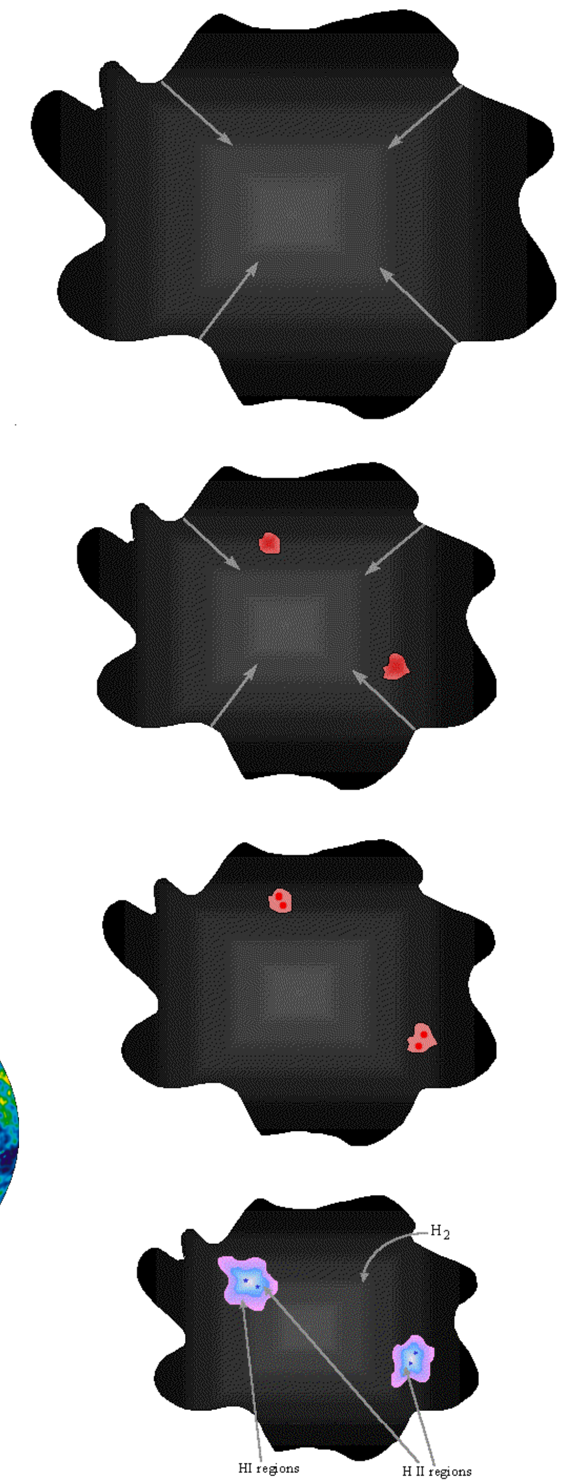
From λ = 30 μm to λ = 3 mm

Astrophysical interests



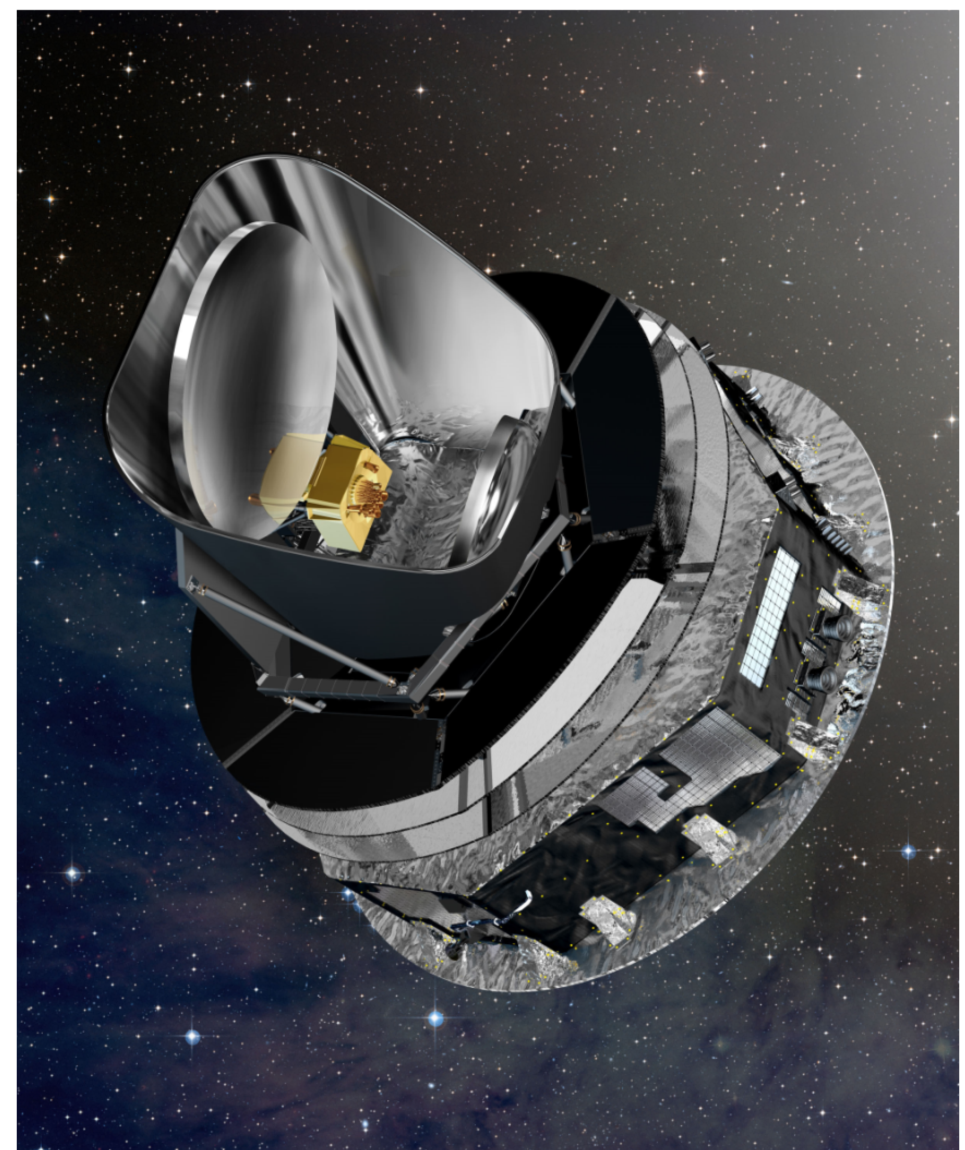


- Cold thermal phenomena (< 100 K)
  - molecular clouds
  - outer solar system
- Cosmic microwave background at ~3 K
  - thermal radiation from early Universe (recombination), predicted by Big Bang theory



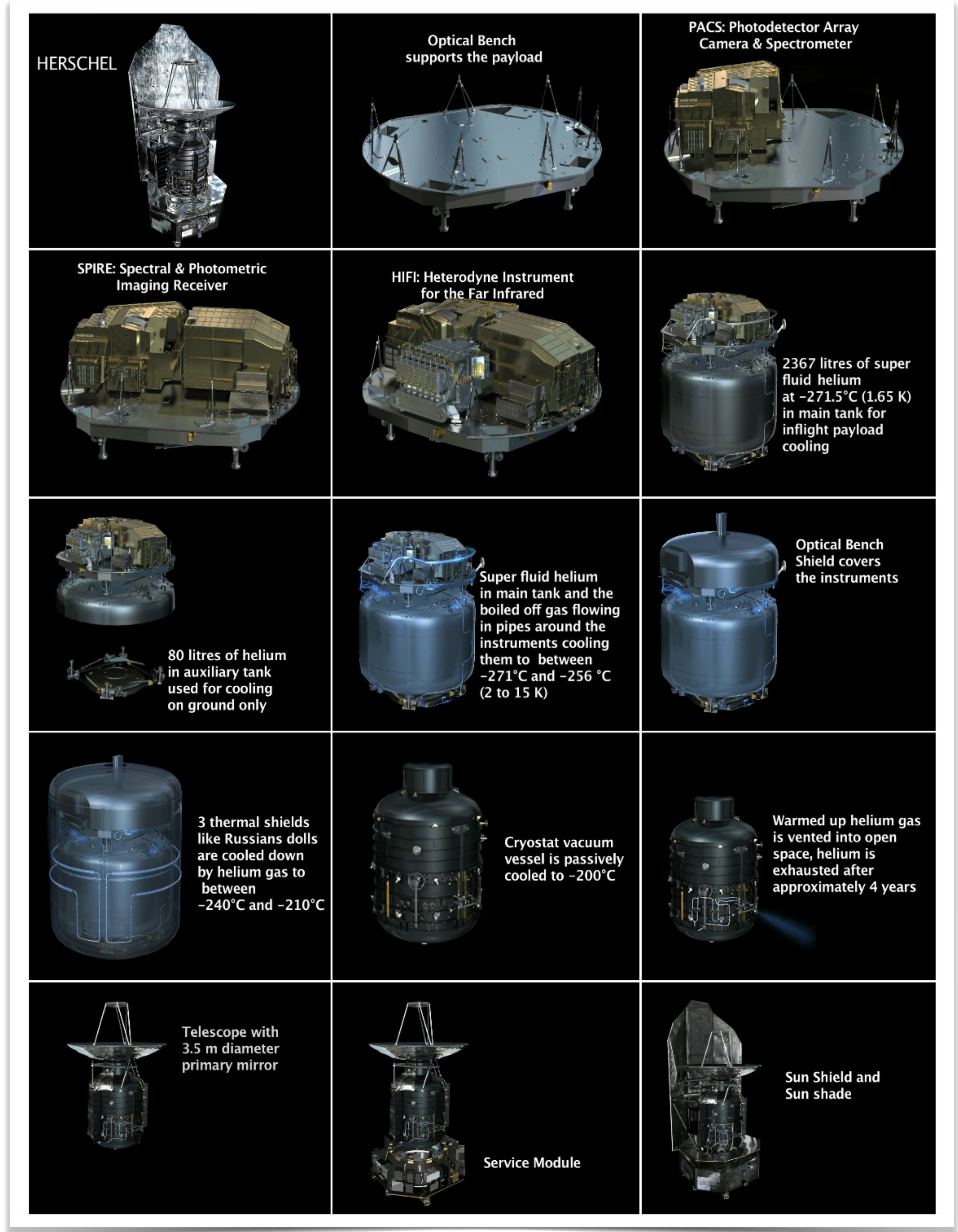
Examples: Herschel & Planck

- ESA missions, launched together by Ariane V (May 2009)



Herschel

- Diameter: 3.5 m (SiC)
- Wavelengths: 55 to 672 μm
- Size: 7.5 x 4 x 4 m
- Weight: 3.4 tons
- Orbit: Lagrange L2
- Duration: 3.5 years
- Cooling: a few Kelvins



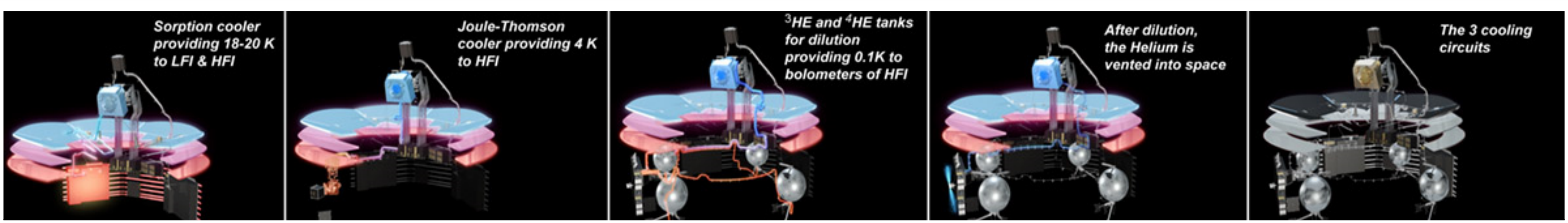
Planck

- ✦ Diameter: 1.5 m
- ✦ Range: 0.3 to 10 mm
- ✦ Size: 4.2 m (cube)
- ✦ Weight: 1.9 tons
- ✦ Duration: 2 years (2 full sky surveys)

Cooling

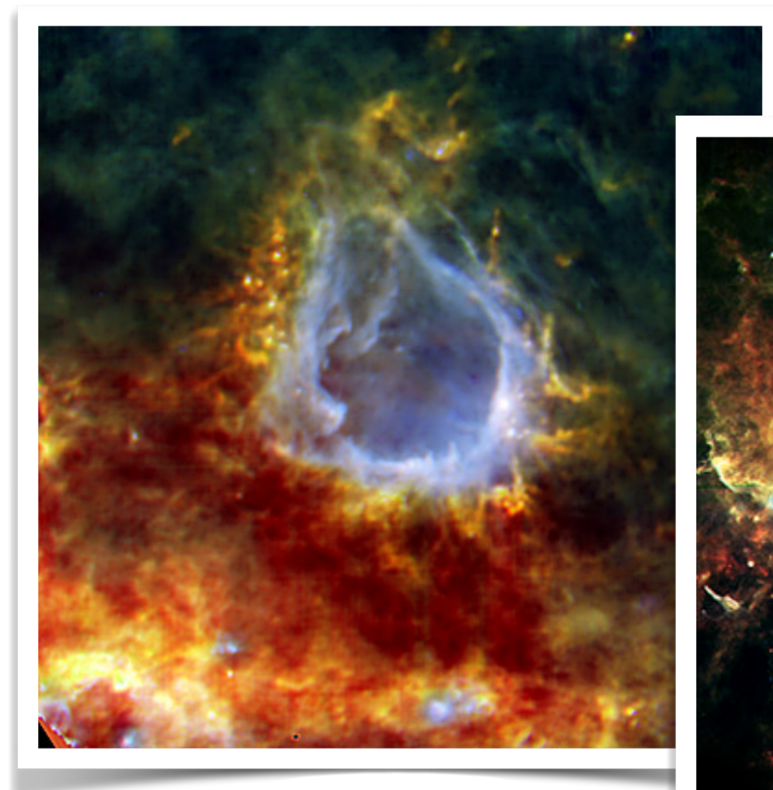
Tests @ CSL

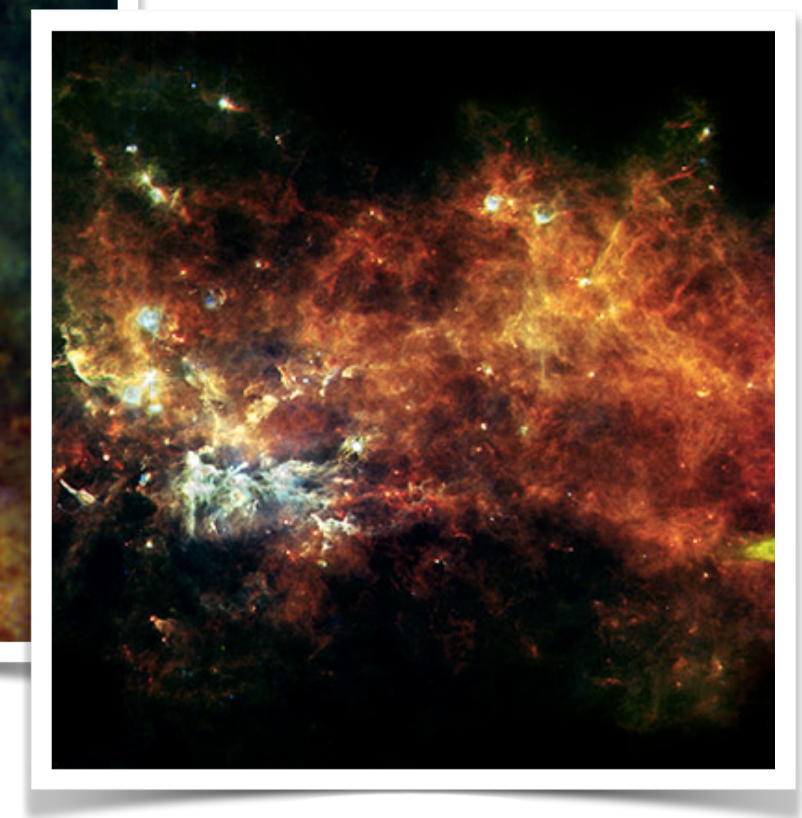
- ✦ Telescope: 15 - 20 K
- ✦ Focal plane: 5 - 6 K
- ✦ Bolometers: 0.1 - 0.3 K
- ✦ Several cooling agents
  - sun shield / baffle
  - hydrogen sorption cooler
  - Helium Joule-Thomson cooler (frictionless pump)
  - $^{3}He/^{4}He$ dilution cooler
- ✦ Extreme stability (~0.01 K level)

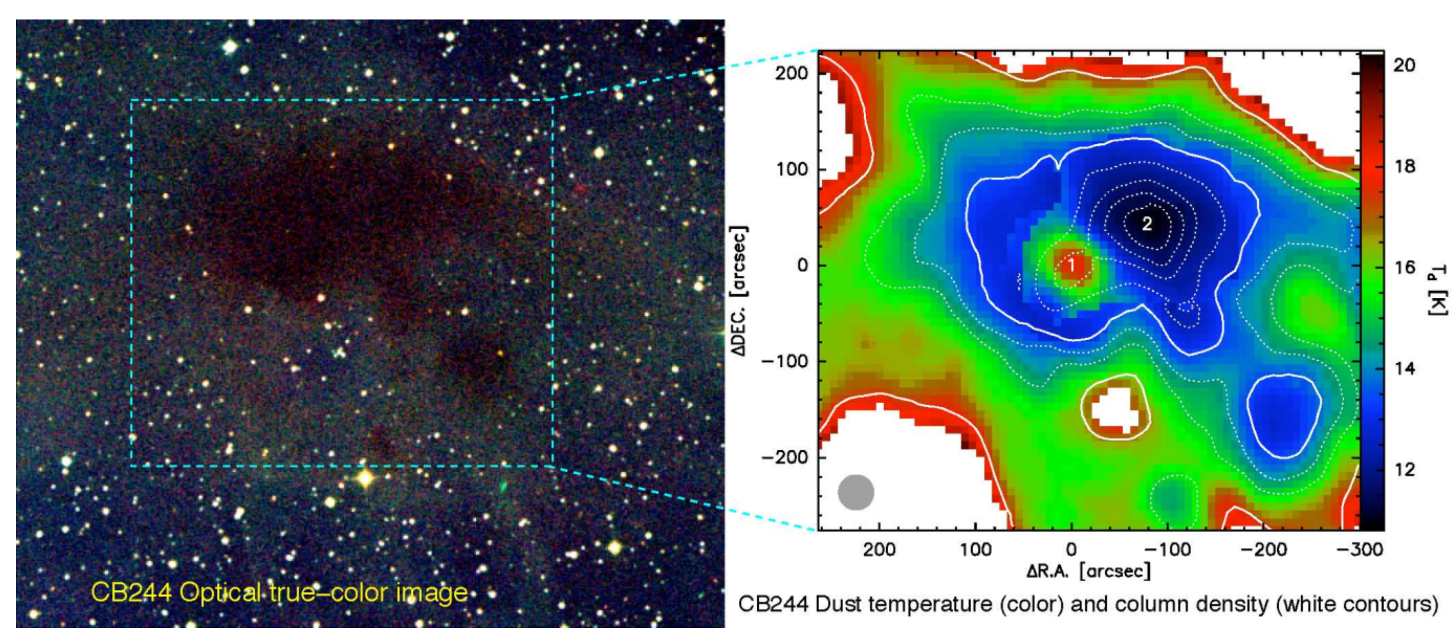


Herschel results

- ✦ Assembly of the first galaxies (starburst galaxies)
- ✦ Star formation
  - massive stellar embryos found in filaments across our galaxy
- ✦ Mass loss of evolved (dying) stars
- ✦ Molecular chemistry
  - in cold molecular clouds (H_2O, O_2, complex organics)
  - planetary surfaces and atmospheres
  - composition of comets (e.g., deuterium content)





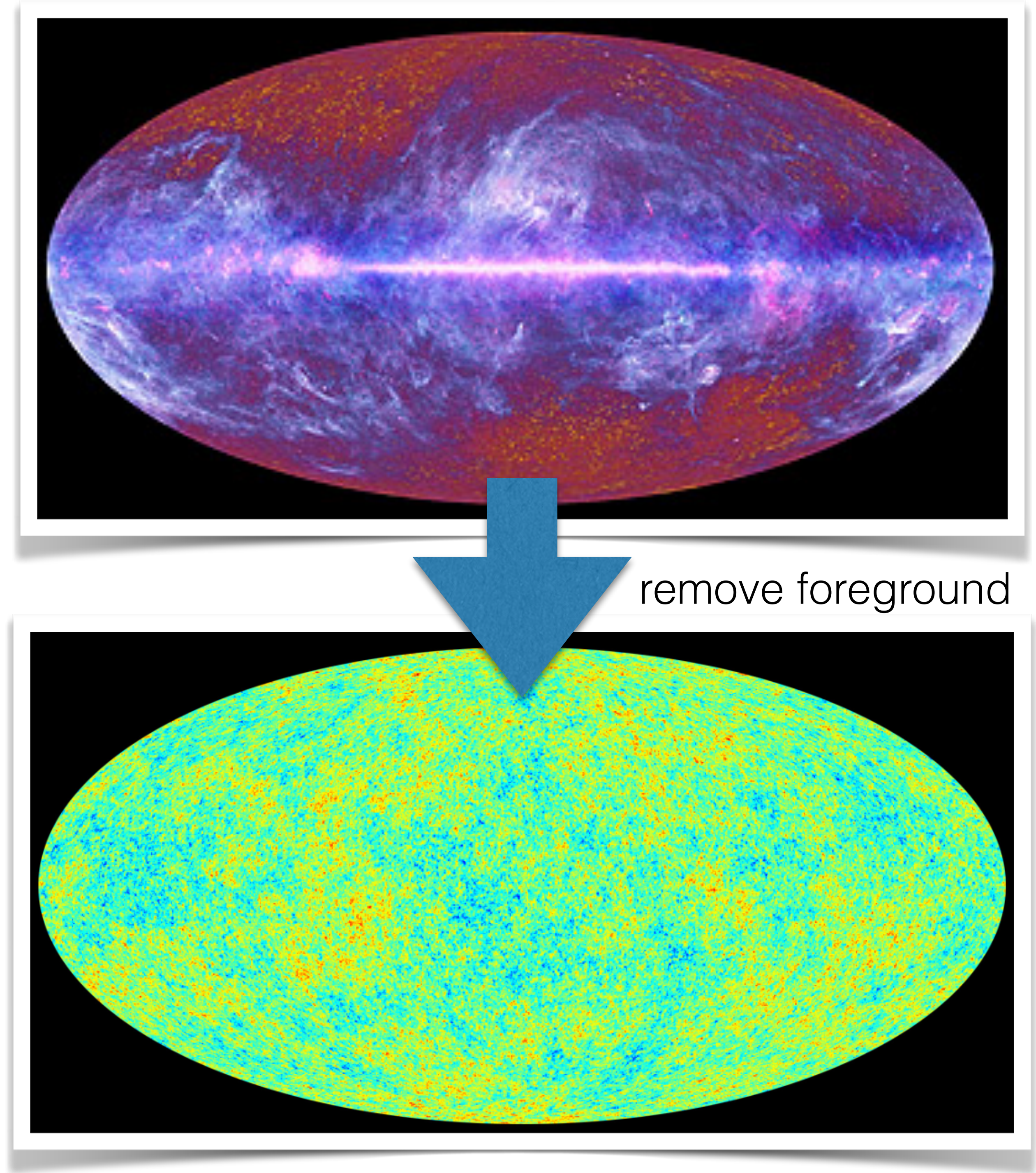


CB244 Optical true–color image

CB244 Dust temperature (color) and column density (white contours)

Planck results

- CMB at 2.7 K
  - anisotropies measured at the $\Delta T/T=10^{-6}$ level
  - unprecedented angular resolution (5 arcmin)
- Large scale properties of the Universe
  - 26% content of dark matter (5% ordinary matter)
  - clumps and the origin of large scale structures
- Validation of inflation models



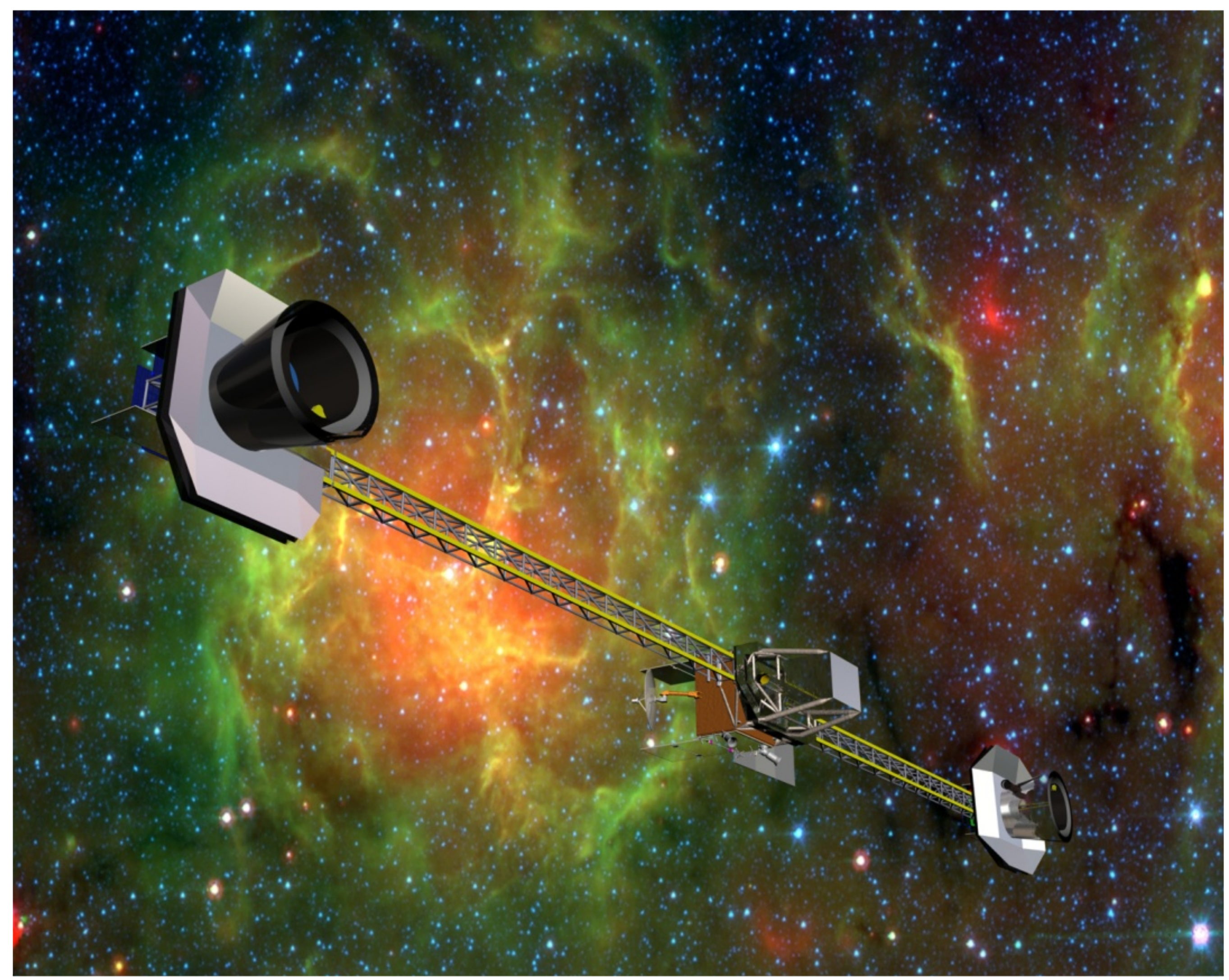
Other example: SOFIA

- 2.5 m telescope
- Altitude > 13 km
- Range: 300 nm - 1.6 mm
  - mostly 5 - 300 μm
- Modified Boeing 747-SP
  - reinforced structure for 20-ton telescope
  - big hole in fuselage, avoiding turbulence!

SOFIA open-door flight test

Future: interferometry

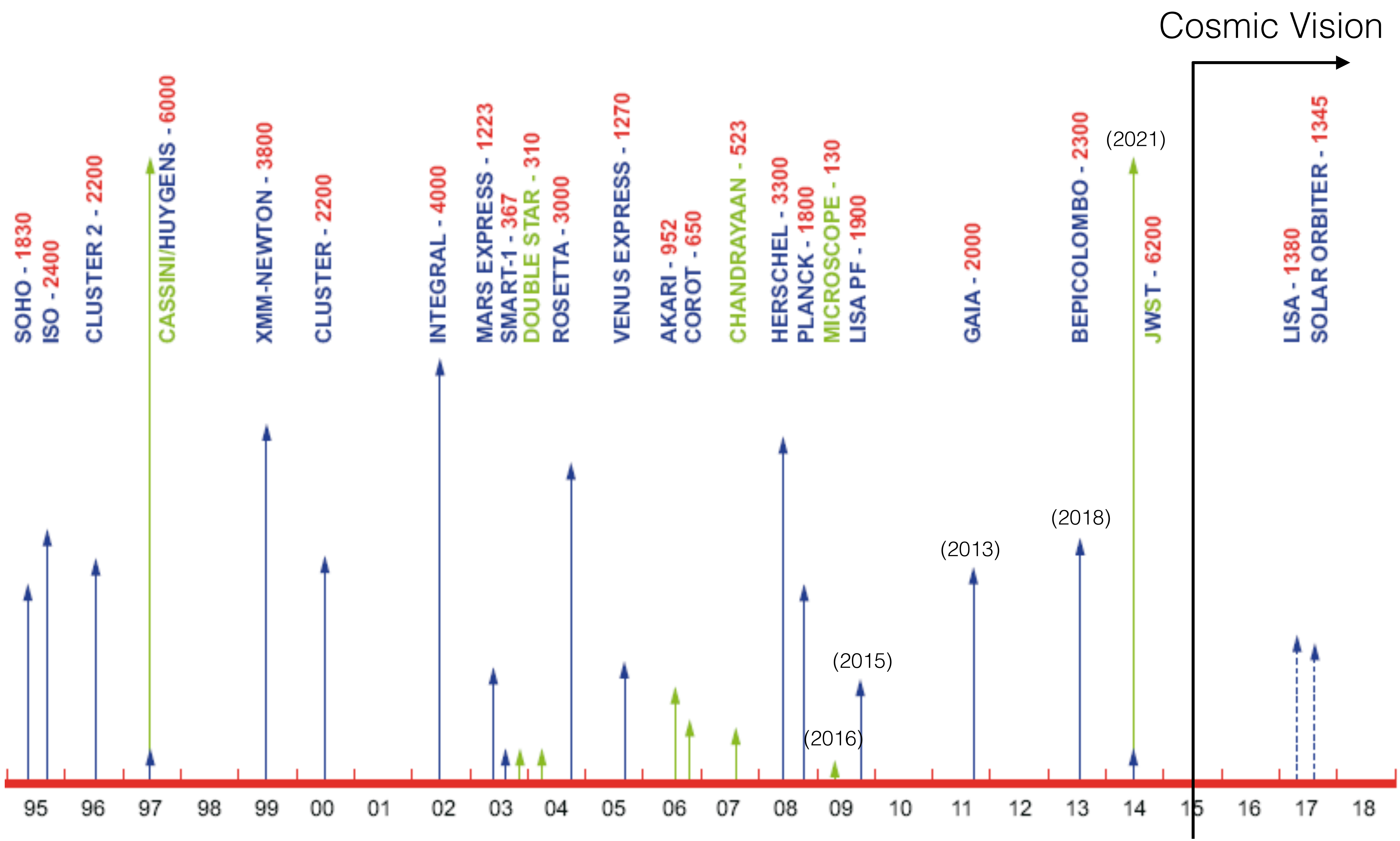
- Illustrated here: SPIRIT concept (formation flying also considered)
- Baselines: 7 - 35 m (deployable)
- 1-m class telescopes
- Range: 25 - 400 μm
- Cooling
  - optics at 4 K
  - bolometers at 50 mK
- Aperture synthesis
  - array: sliding & rotation



Cosmic Vision 2015-2025

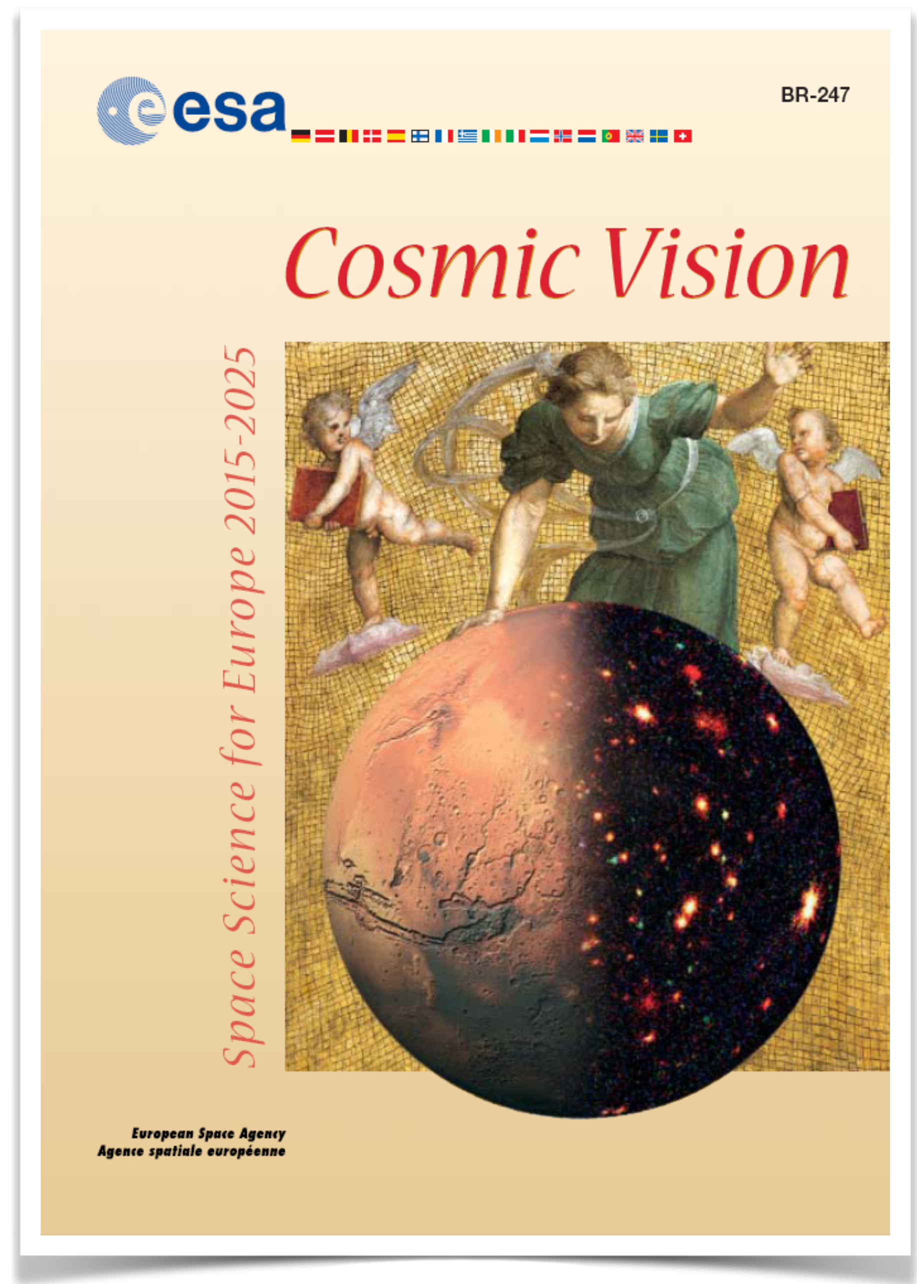
The ESA scientific program

Horizon 2000+ program



Cosmic Vision

- Four themes
  - What are the conditions for planet formation and the emergence of life?
  - How does the Solar System work?
  - What are the fundamental physical laws of the Universe?
  - How did the Universe originate and what is it made of?
- Several mission opportunities



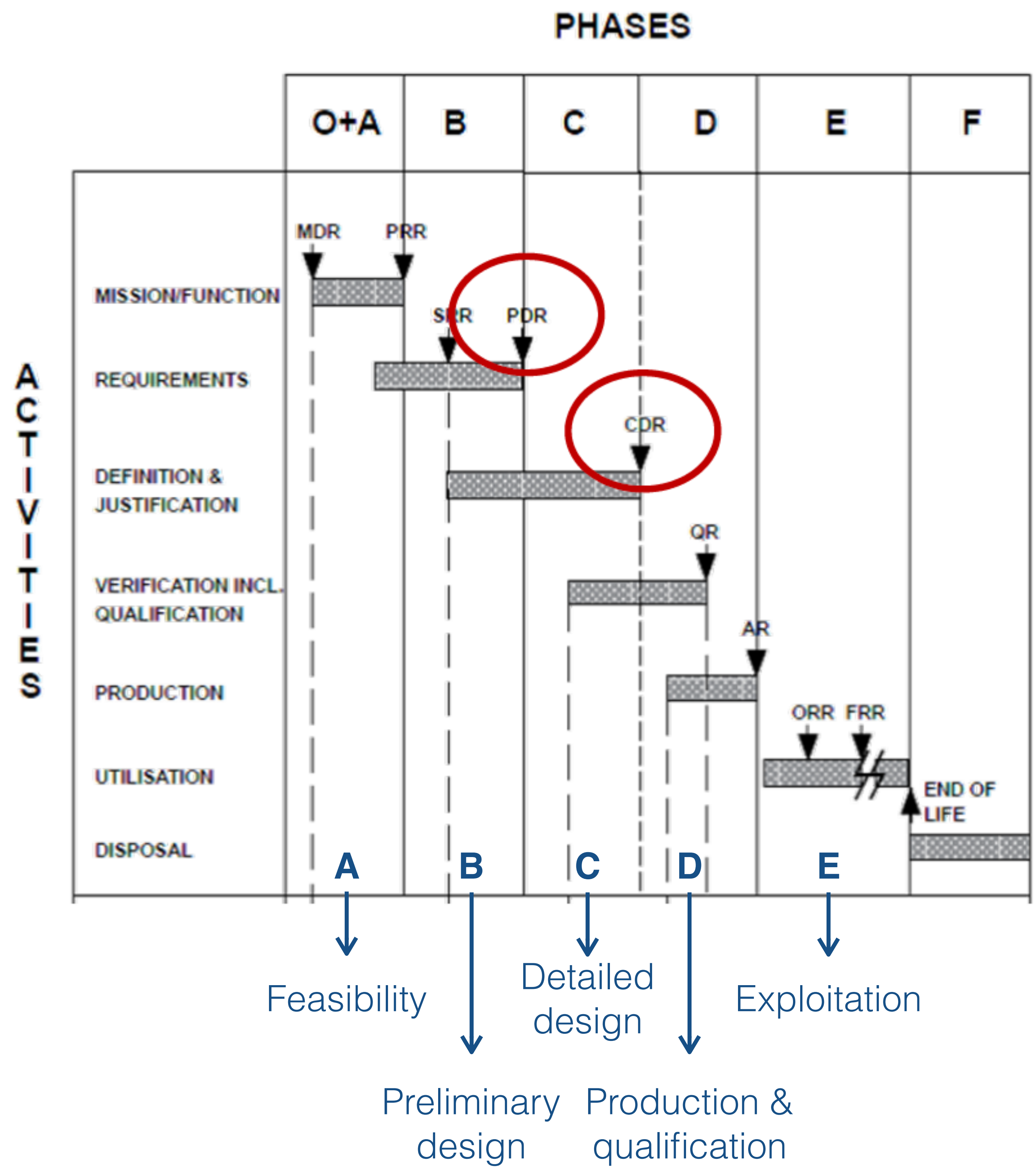
Mission opportunities

- Three classes of missions
  - Large missions (~900 M€, ESA contribution)
  - Medium missions (~500 M€, mostly stand-alone)
  - Small missions (~50 M€, ESA contribution)
- Several calls for mission concepts
  - 2007: one Large (L1, 2022) and two Medium (M1-M2, 2019-2020)
  - 2010: one Medium (M3, 2026)
  - 2012: one Small (S1, 2018)
  - 2013: two Large (L2-L3, 2028-2034)
  - 2015: one Medium (M4, 2028), one Small (S2, 2021)
  - 2016: one Medium (M5, 2032)

Call for mission #1 (M1, M2, L1)

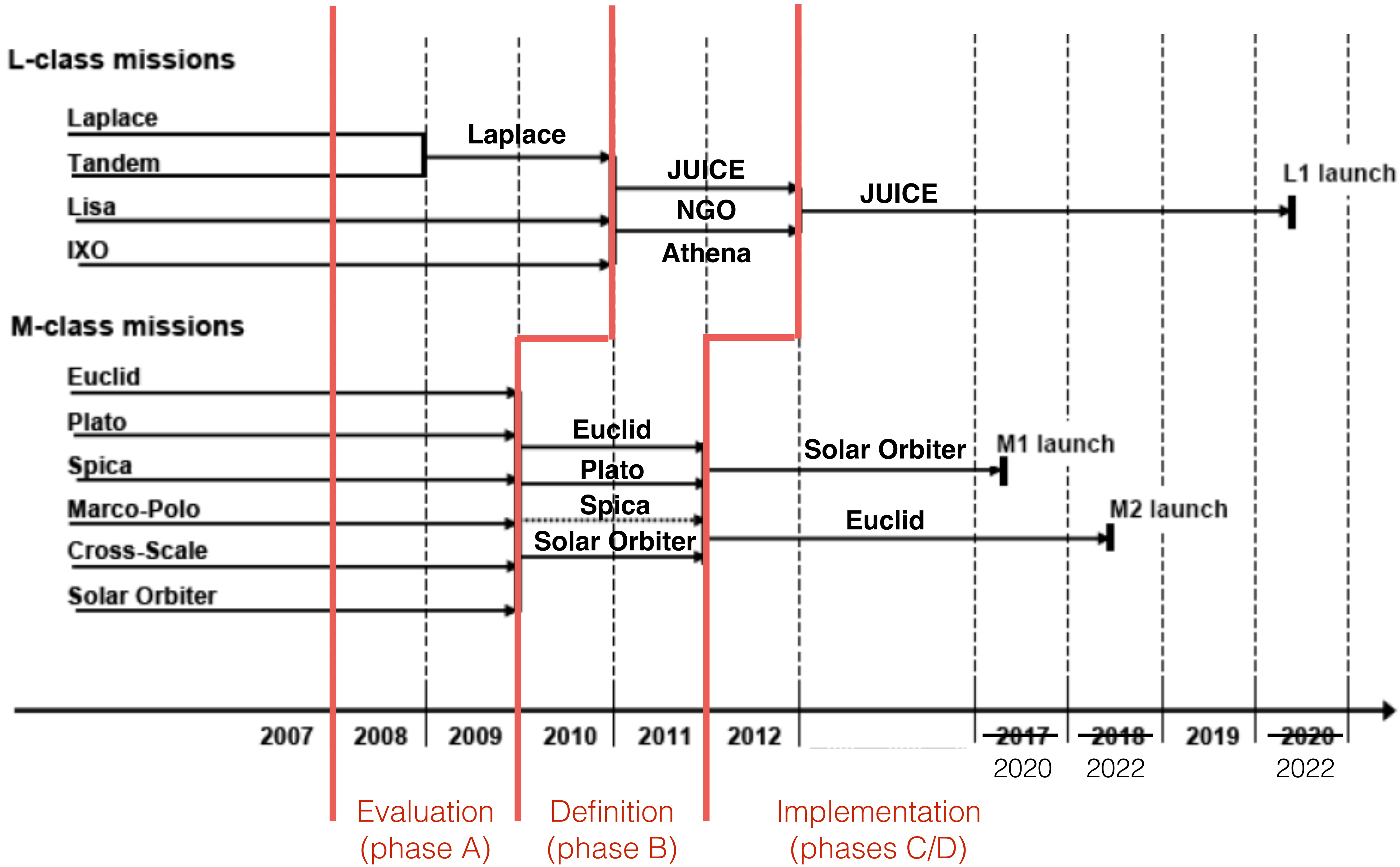
- 6 M-class missions pre-selected for study
  - Euclid (dark energy, lensing)
  - Plato (exoplanets)
  - Spica (IR observatory, JAXA collaboration)
  - Marco-Polo (asteroid sample return)
  - Cross-Scale (magnetosphere, shock waves)
  - Solar Orbiter (Sun at high resolution - Horizon 2000+)
- 4 L-class missions pre-selected for study (NASA collaboration?)
  - Laplace (Jupiter-Europe system)
  - TandEM (Saturn-Titan-Enceladus system)
  - IXO (X-ray observatory)
  - LISA (gravitational waves - Horizon 2000+)

Phases of a space project



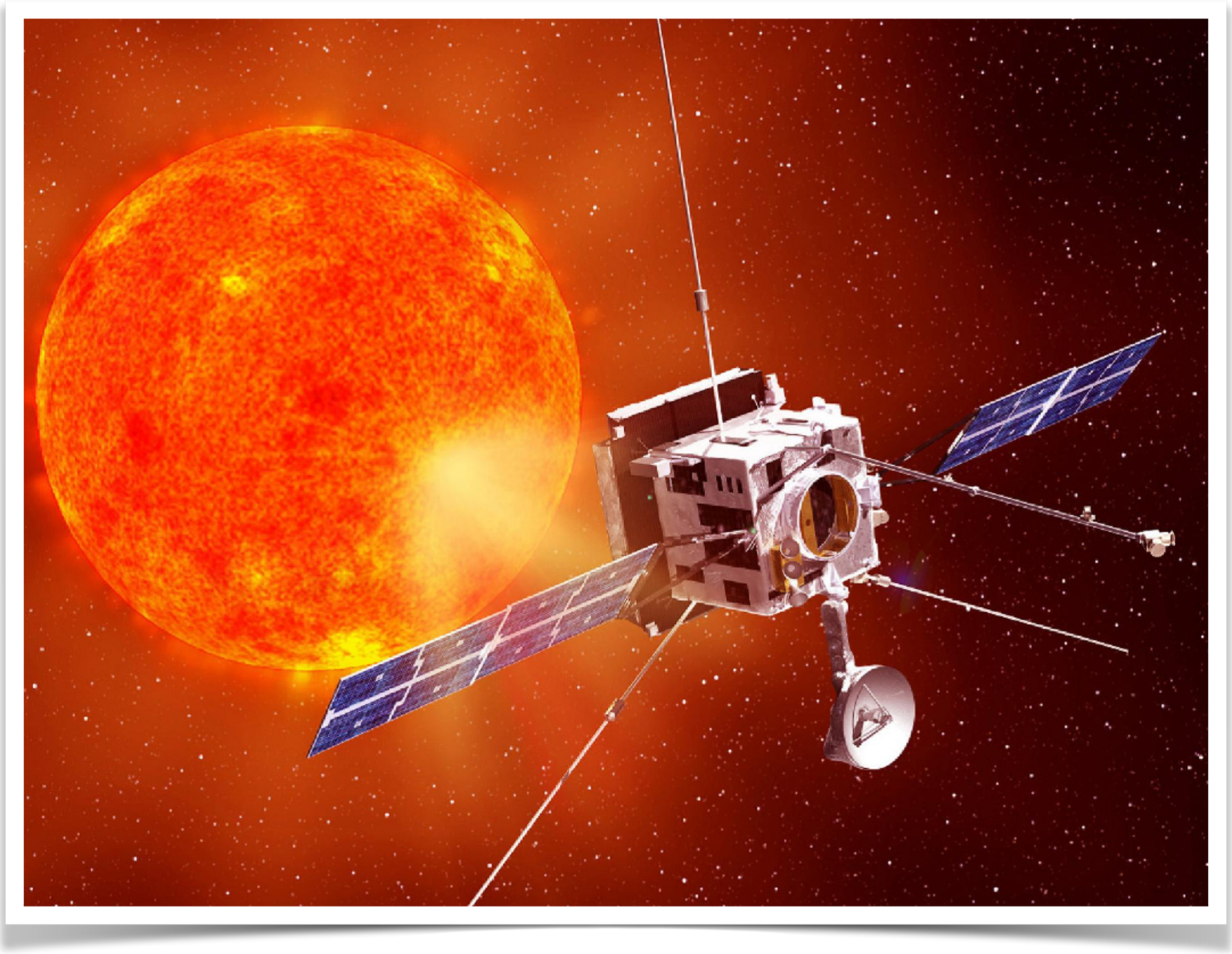
AR = Acceptance Review
CDR = Critical Design Review
FRR = Flight Readiness Review
MDR = Mission Definition Review
ORR = Operational Readiness Review
PDR = Preliminary Design Review
PRR = Preliminary Requirements Review
QR = Qualification Review
SRR = System Requirements Review

Selection process



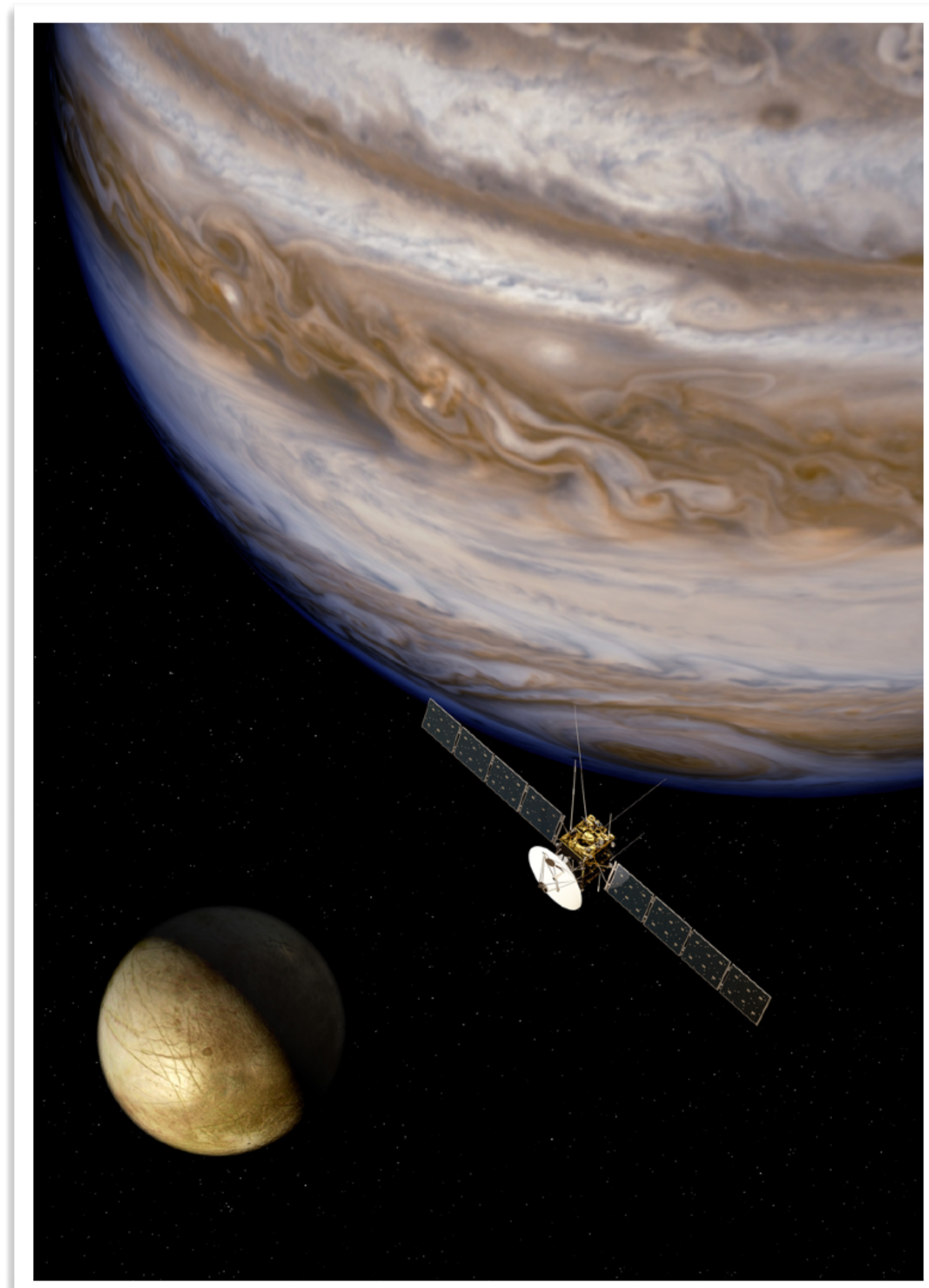
Solar Orbiter

- Orbit at 1/4th of Sun-Earth distance
- Heat shield to reduce temperature from 600°C outside to 60°C inside spacecraft
- One of the instruments (EUI) built by CSL



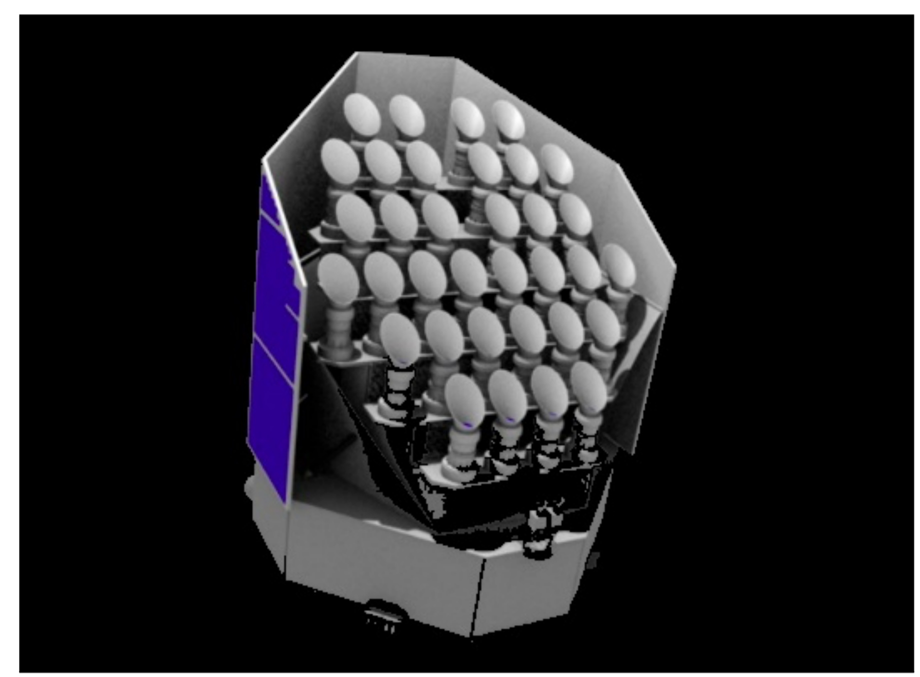
JUICE

- Mission to the Jupiter icy moons (Ganymede, Europa, Callisto)
- More challenges
  - power budget and solar panels (97 m^2!!!)
  - radiation tolerance (Jupiter magnetosphere)
  - mass budget (10 instruments)
  - orbital dynamics (flybys)
  - communications
  - planetary protection (sterilization)



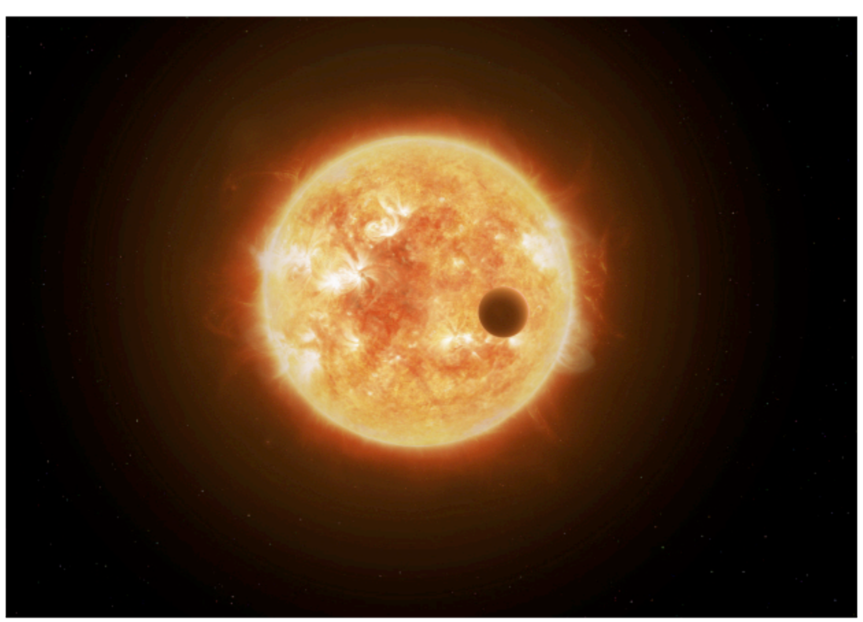
Call for mission #2 (M3)

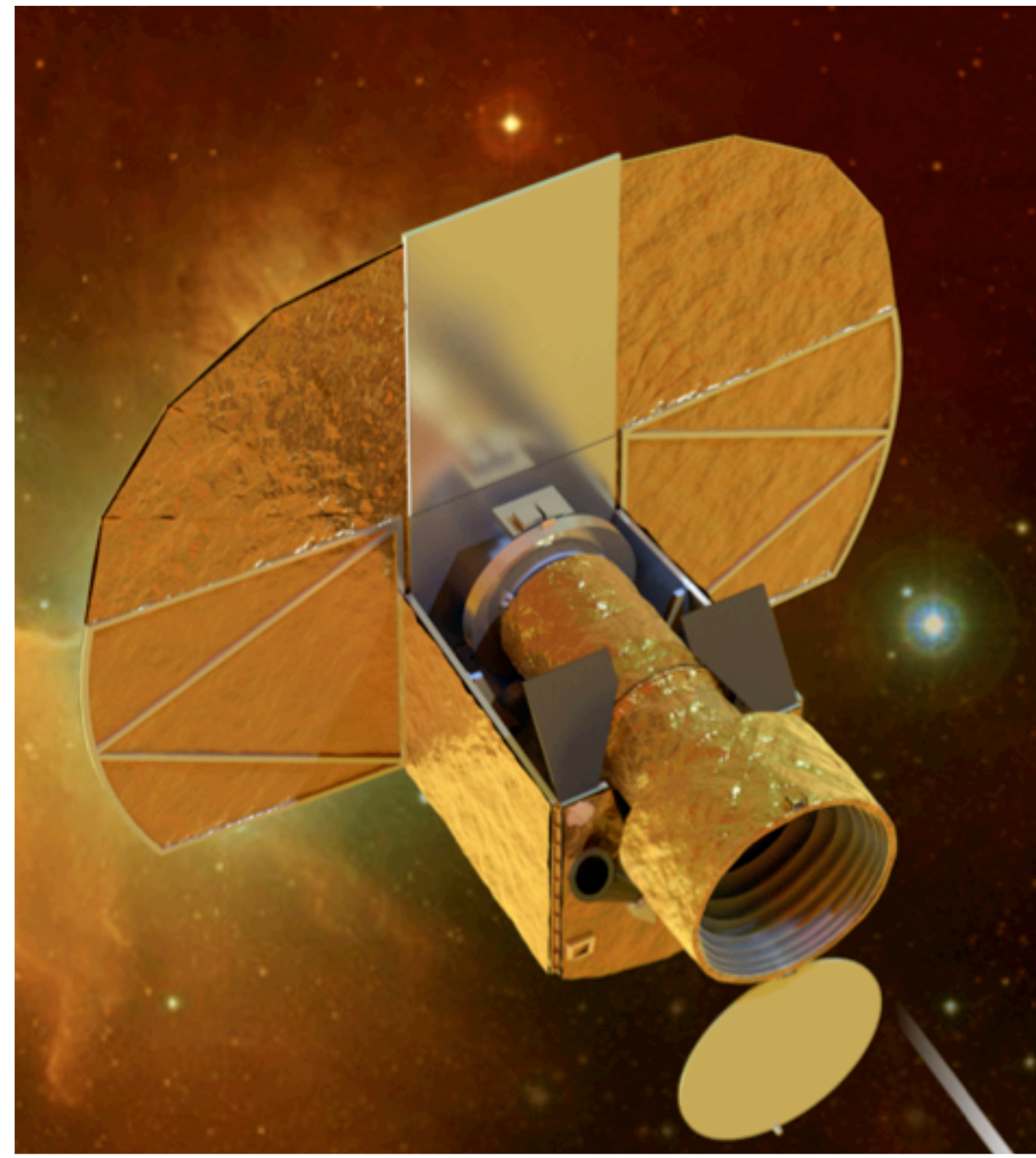
- Four (out of 47) M-class missions selected for assessment
  - EChO: Exoplanet Characterization Observatory
  - PLATO: PLAnetary Transits and Oscillations of stars
  - LOFT: Large Observatory For X-ray Timing
  - STE-QUEST: Space-Time Explorer and Quantum Equivalence Principle Space Test
- Down-selection (2014): PLATO
- Launch expected in 2026



Call for missions #3 (S1)

- Cost to ESA: 50 M€
- Max total cost: 150 M€
- 26 proposals submitted
- CHEOPS selected
- Launched in Dec 2019

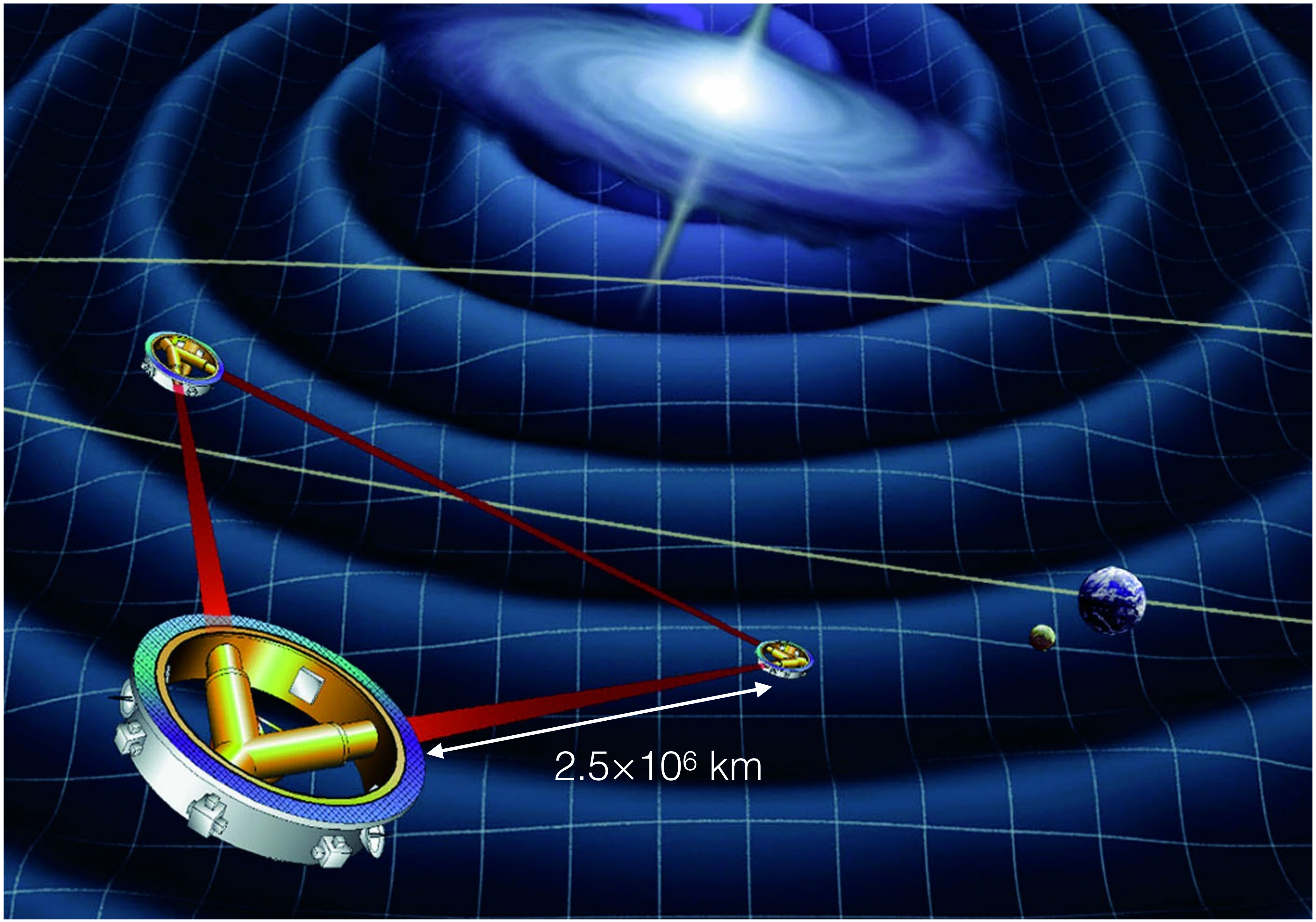




L2 & L3 missions

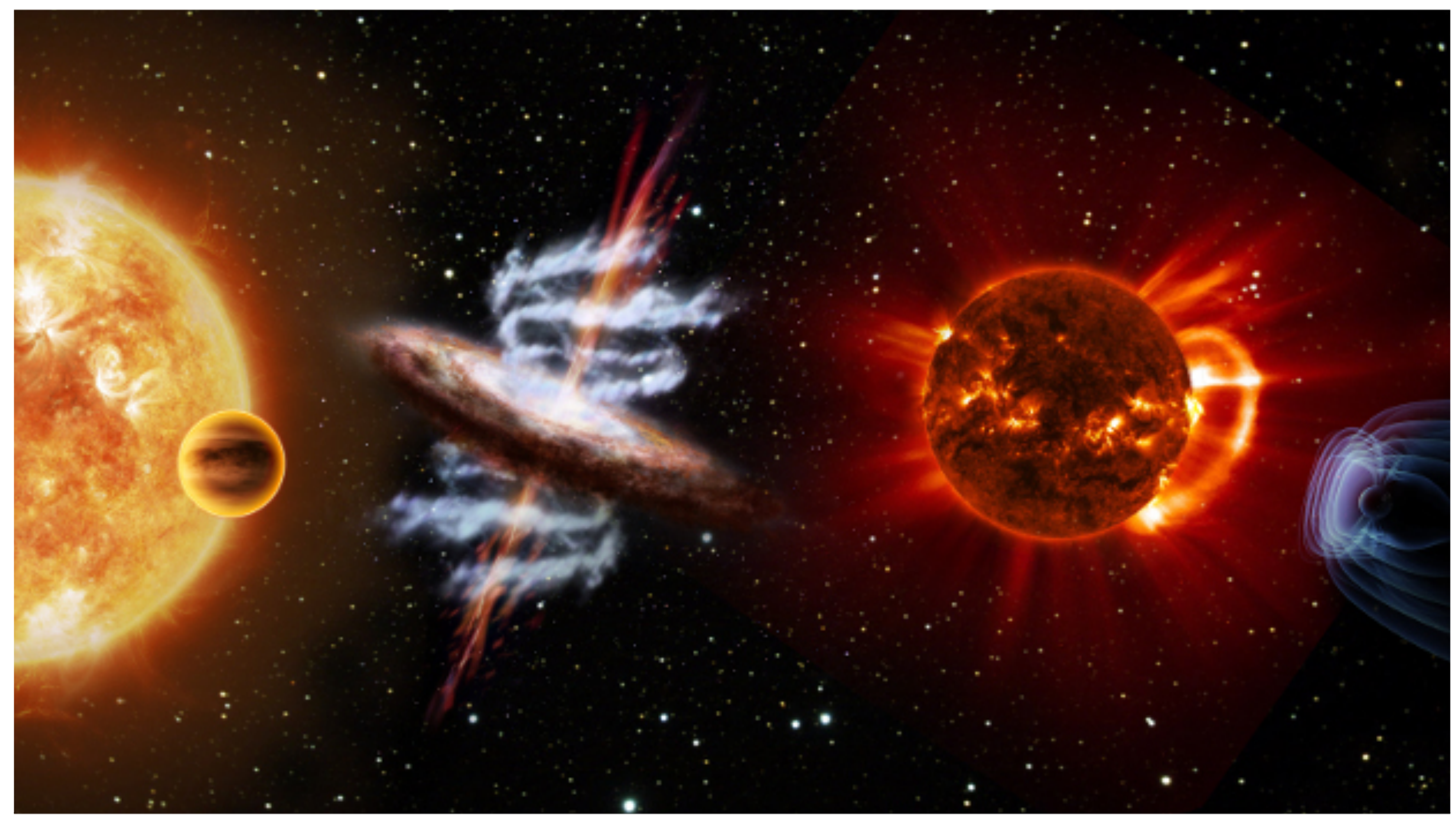
- Themes selected by ESA working groups in 2013
  - L2: the hot and energetic universe (2031)
  - L3: the search for gravitational waves (2034)
- L2 mission concept selected in 2014: ATHENA (Advanced Telescope for High Energy Astrophysics)
- L3 mission concept confirmed in 2017: LISA (Laser Interferometer Space Antenna)
  - does not rely on electromagnetic radiation any more!

LISA: gravitational waves



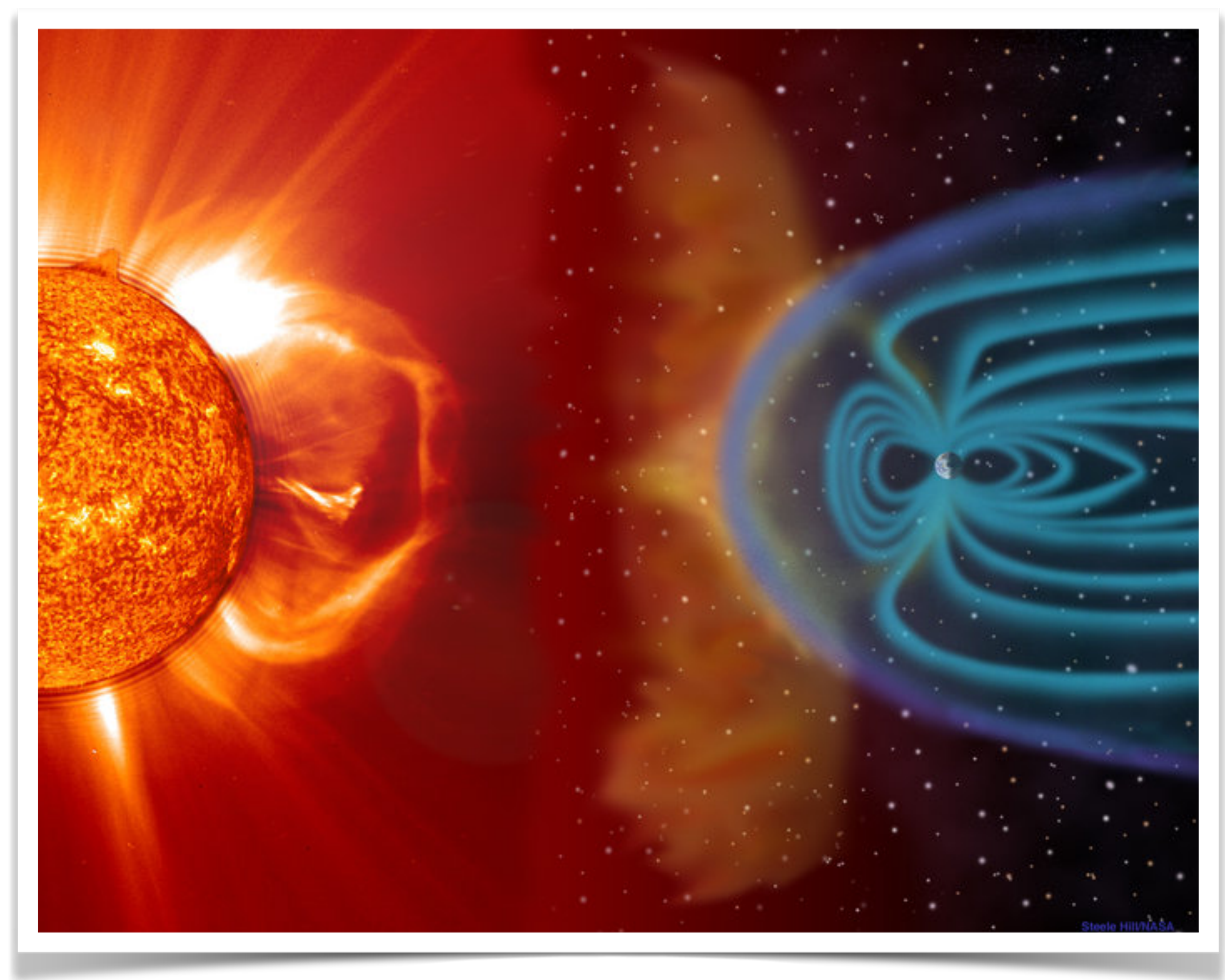
Call for Missions #4 (M4)

- Three (out of 27) candidates selected in June 2015
  - ARIEL: Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (≈EChO)
  - THOR: Turbulence Heating ObserveR
  - XIPE: X-ray Imaging Polarimetry Explorer
- ARIEL selected Nov 2017
- Planned launch: 2029



Call for Missions #5 (S2)

- Special call for missions in partnership with China
  - shared participation of both agencies
- 13 proposals received
- SMILE selected
  - interactions between the Earth magnetosphere and the supersonic solar wind
- Launch: 2025

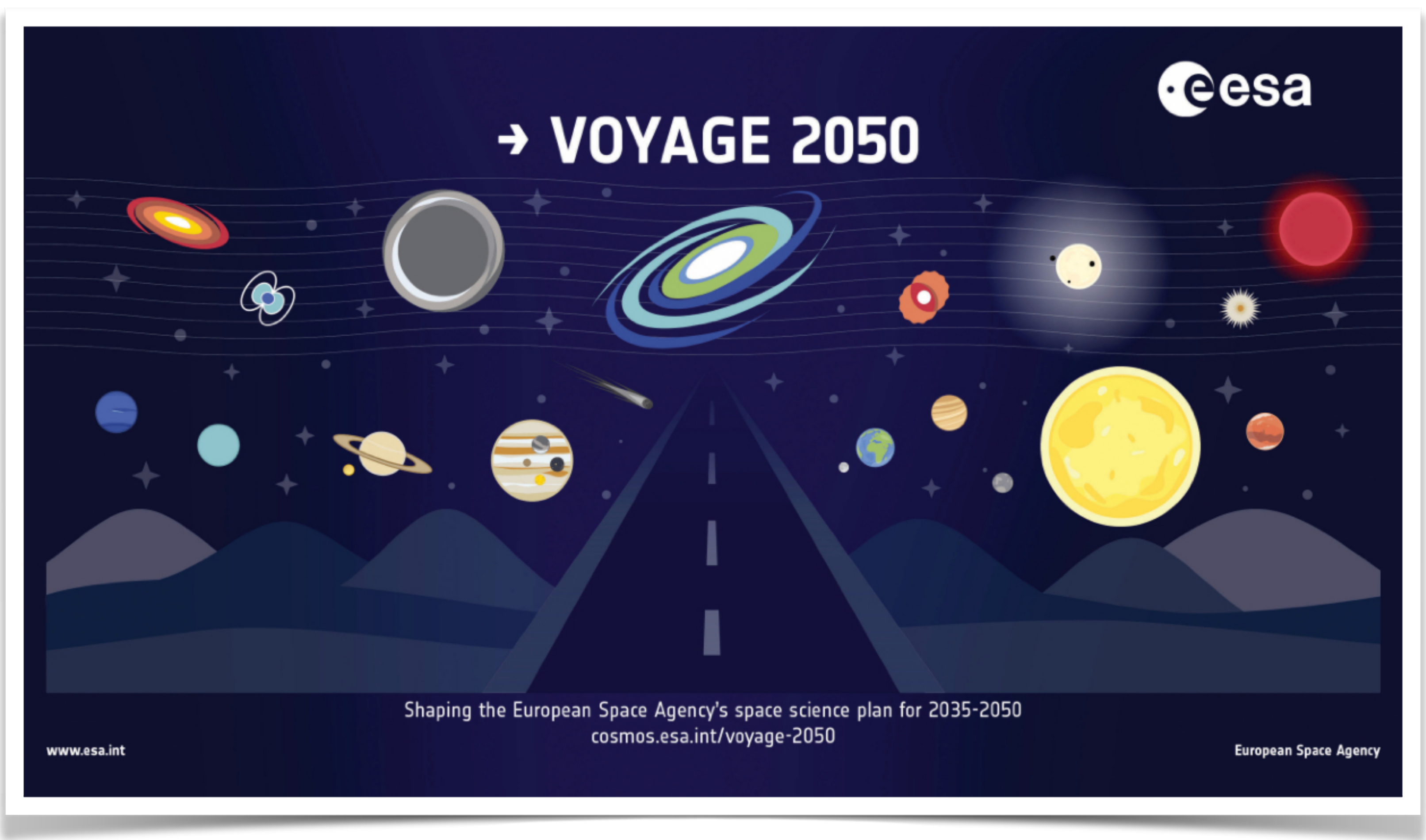


Latest call: M5

- Call released in April 2016
- Selection of missions for study: May 2018
  - ~~SPICA: far-infrared telescope~~
  - THESEUS: ɣ-ray / X-ray telescope
  - EnVision: Venus orbiter
- Phase A completed in 2021, leading to selection of EnVision. Now entering Phase B (preliminary design).
- Planned launch date: 2032

Next program: Voyage 2050

- Top priorities for large missions already identified:
  - moons of the giant planets (habitability)
  - from temperate exoplanets to the Milky Way (rocky planets)
  - new physical probes of the early Universe (gravitational waves)



Want to contribute?

Masters thesis at STAR Institute

Ground- and space-based instrumentation (incl. at CSL)

data analysis / scientific exploitation

contact: Michaël De Becker <michael.debecker@uliege.be>